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SURVIVABILITY OF INTERDICTION AIRCRAFT:
SENSITIVITY TO TERRAIN FOLLOWING,
COMMAND ALTITUDE, VELOCITY, AND
ELECTRONIC COUNTER MEASURES

THESIS

AFIT/GOR/MA/82D-2 Mark D. Reid
1LT USAF

SCHOOL OF ENGINEERING

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

Mark D. Reid

1LT USAF

Graduate Operations Research

December 1982

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Preface

I initially became interested in the problems of aircraft vs. defensive ground threat modeling while at my first Air Force assignment at the Tactical Fighter Weapons Center. The exposure I received to the existent modeling there was varied, but superficial. Carrying out a literature review and in-depth survivability analysis offered an opportunity to increase my exposure to the current SAM and AAA modeling and satisfy AFIT's requirements for a thesis.

My research and literature review indicated a paucity of models that addressed terrain following penetrators and generated probability of kill data. Talks with Air Force Studies and Analysis confirmed this need: my thesis goal became to produce a framework with which to study terrain following flight paths and provide survivability data.

The process of compiling this thesis has been, at the least, educational. I'd like to thank Mike Breza, John Kordik, and particularly Frank Campanile, all of ASD/XR, for their assistance. It was a pleasure to work with such an able group. My thanks to Ted and Gail Fraley for their help with airplanes and commas. Special thanks to L/C Jim Bexfield for his advice and inspiration, and for making this entire exercise and institution worthwhile.

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Abstract

The FORTRAN program TERRAIN is a deterministic model of a tactical aircraft penetrating a Surface-to-Air (SAM) and Anti-Aircraft Artillery (AAA) threat. TERRAIN generates a terrain following flight path profile based on specified flight parameters and then assesses the aircraft vulnerability in terms of exposure time and shots taken by individual threat site and the total defense.

Modifications were made to assess aircraft survivability (the probability of kill of the aircraft) and to calculate the effect on the probabability of kill of electronic countermeasures. The TERRAIN model is particularly sensitive to the selection of beddown, rate of fire for AAA, aircraft velocity, and aircraft commanded clearance altitude.

A comparison of the strengths and weaknesses of the original TERRAIN model, the modified TERRAIN model, and six other SAM/AAA models has been compiled. A user's guide for the modified TERRAIN model is provided.

SURVIVABILITY OF INTERDICTION AIRCRAFT: SENSITIVITY TO TERRAIN FOLLOWING, COMMAND ALTITUDE, VELOCITY, AND ELECTRONIC COUNTER MEASURES

I Introduction

Background

During conventional armed conflict, the eventual outcome is decided by relative changes in the Forward Edge of the Battle Area (FEBA) and by which side controls more physical area. Area control is affected by ground units. Friendly air forces insure that enemy air forces do not interfere with the actions of ground units as they operate. It is the presence and effectiveness of this air support which allows the outcome of the battle to be decided on the ground. Air support is manifested in three primary missions: counter air, close air support (CAS), and interdiction. While involved in CAS, aircraft operate relatively close to the FEBA. While acting in this role, air forces are faced with anti-aircraft artillery (AAA) and surface-to-air missile batteries (SAM) indigenous to the units clustered about the FEBA. Aircraft assigned the interdiction mission must penetrate the FEBA, ingress to the target, deliver munitions, and then egress. During

this process, the aircraft face enemy air interceptors, ground based air defense units (generically referred to as ADU from this point on) indigenous to maneuver units, and independent, self-contained ADU deployed well behind the FEBA. The critical question which faces these penetrators is how to avoid ADU (both air and ground types), accomplish the interdiction mission, and return safely.

Situation

The scenario that is generally considered when studying ground and air warfare effectiveness is the European theatre. The U.S. aircraft types tasked with interdiction in NATO are the F-111, F-4, F-15, and F-16. Each of these aircraft operate with different tactics (combinations of flight altitude, velocity, ingress/egress method, reaction to threat, etc.), missions, and performance regimes. They do face the same types of threat.

When flying an interdiction mission, the aircraft must survive both ground and airborne threats. My concern lies with the ground threat. The Warsaw Pact forces currently have SA-2, SA-3, SA-4, SA-6, SA-7, SA-8, SA-9, and SA-11 surface-to-air missiles deployed. These missiles vary in range, type of guidance (radar, infra-red), altitude, and maneuverability. The Warsaw Pact (WP) forces also have deployed various types of AAA

including the ZSU 23-4, 57mm, 85mm, and 130mm. These SAM and AAA units are deployed in relatively fixed positions (areas of approximately 25 square km), which are fairly well known through intelligence sources. Figure 1-1 displays a typical SAM site set-up. There are a variable number of TELs (transporter erector launcher) at each site. Each TEL has a variable number of rails on which missiles are mounted. TELs may or may not have collocated radars (see Figure 1-1). Those TELs not possessing a collocated radar will generally be netted in some manner with an external radar. The number of TEL's at a site, the number of rails on each TEL, and the number of TELs possessing radar will vary by missile type and equipment limitations. Types may even vary within a site. The large numbers of SAMs and AAA guns deployed and their varied characteristics presents a complex threat to a penetrator.

The discussion above allows a more specific problem to be identified: what tactics should a penetrator employ in order to increase his chances of evading the ADU threat and to successfully perform his mission?

Commonly used tactics for interdiction aircraft in the past required that the penetrator fly low and fast. The pilot is able to take advantage of local geography to mask him from ADU acquisition radars when he flies low. In addition, some radars have a minimum downlook angle.

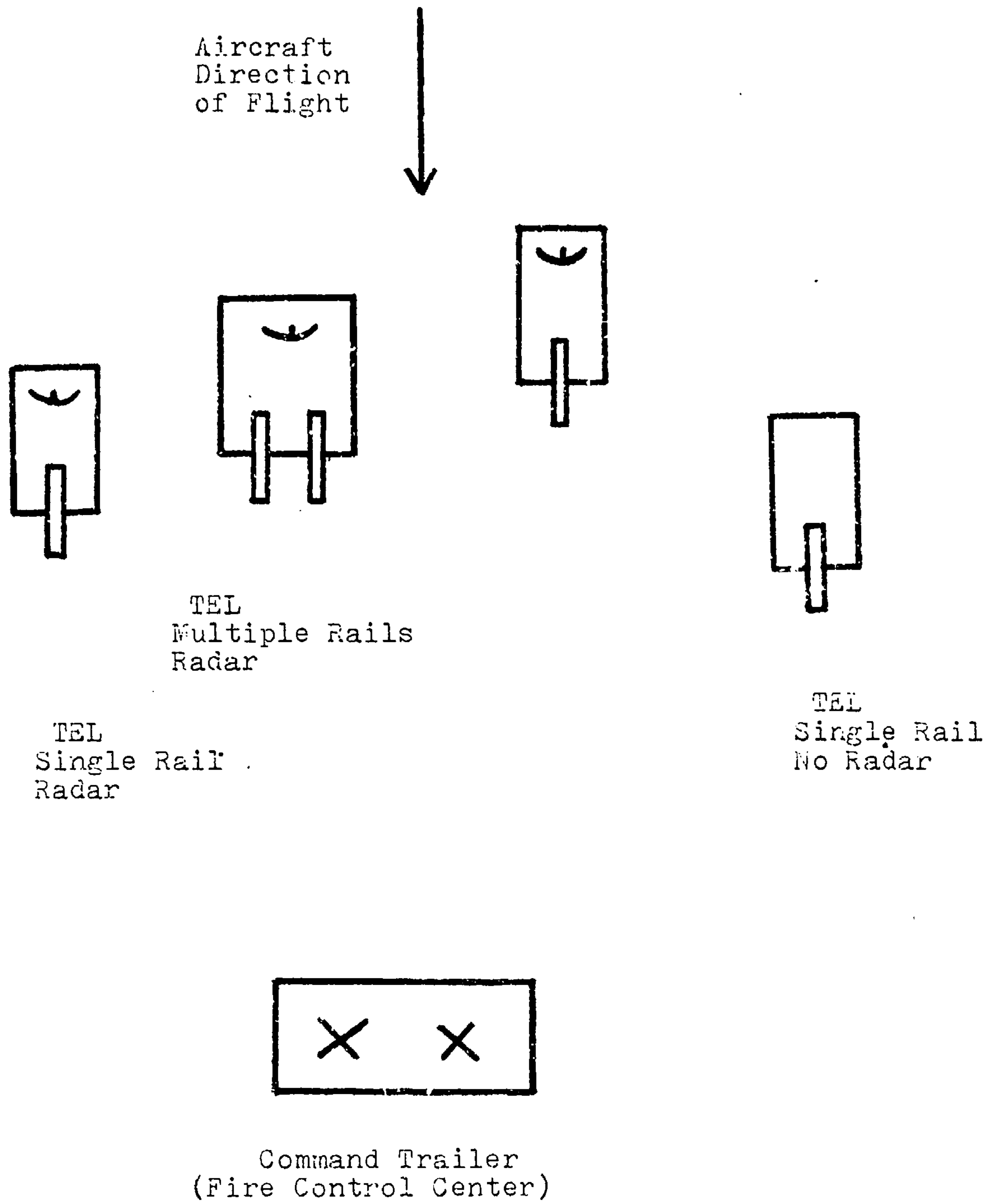

Figure 1-1 Sample SAM Site Set-Up

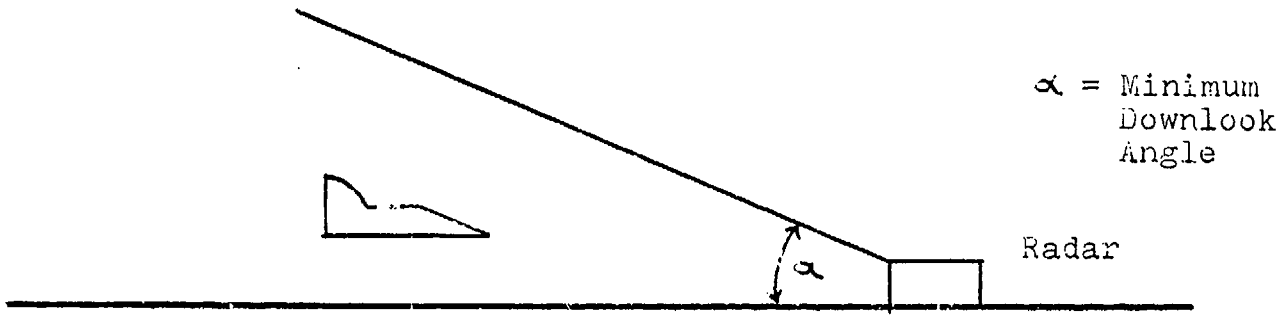

Figure 1-2 Minimum Downlook Angle

That is, they cannot look below a certain angle above the horizon. By staying low, the pilot is able to fly below the level of the acquisition radar and avoid any unnecessary exposure. In the cases where the aircraft is actually exposed to an ADU site, the pilot hopes to minimize his exposure time by flying fast and leaving the site's area of coverage as quickly as possible. If the aircraft travels fast enough, it may enter and leave the site's area of coverage before the site has time to react.

The pilot of a low-level penetrator has a choice of how to fly in order to remain out of radar coverage but above the terrain. These choices are Terrain Following (TF) or Terrain Following/Terrain Avoidance (TF/TA). Terrain Following involves flying a nearly straight-line flight path between any two points and adjusting to the underlying terrain only in the vertical plane. That is, the aircraft does not seek to fly around large mountains or use ridge lines or valleys to best advantage, but

merely to maintain a set clearance altitude. Terrain Following/Terrain Avoidance on the other hand will swing around large obstacles while maintaining vertical clearance. This avoids the problem of flying directly over a mountain peak and being temporarily unmasked. After a bearing change, the aircraft must then compensate for that change by either setting a new heading or making a set of corrections to return to the original flight path. The aircraft may be able to utilize TF or TF/TA to find a good tradeoff between velocity and altitude that reduces exposure time. The tradeoff between the two occurs because the terrain the aircraft overflies is not flat and level; it is characterized (especially in the European environment) by hills and valleys. A pilot wants to make the best use of the existing terrain to hide from the ADA radars. He does this by flying fast while staying low and reacting precisely to changes in the terrain. The problem with this is that the pilot cannot tolerate the g forces that would be placed on him by the aircraft's quick violent reactions to changes in the terrain. Aircraft velocity must then be reduced to within the pilot's g limits. This increases the time that must be spent in any one area and increases the chance that some ADU site will be able to lock on. Alternatively, the pilot could increase the command altitude to give the aircraft more room to clear terrain features, thereby affecting the g

level to which the pilot and aircraft would be subjected. There must be a good combination of velocity, tolerable g forces, and command altitude that can be combined with TF or TF/TA capability to minimize the exposure time for an aircraft.

The pilot may employ countermeasures, in addition to velocity and altitude considerations, to defeat the efforts of the threat. These countermeasures can be used against acquisition radars, tracking radars, or homing devices. Electronic countermeasures (ECM) can be used:

1. While the aircraft has not yet been acquired by a site, to prevent that acquisition.

2. After the aircraft has been acquired and the site is attempting to lock on with its tracking radar. Preventing lock-on prevents the site from firing and essentially maintains masking.

3. After lock-on, in an attempt to break lock.

Missile radar guidance is of two types. In the first case, the missile illuminates the target with its own radar, receives the radar reflections directly, and generates the necessary guidance commands internally. ECM is directed at the missile radar in this instance. The second case consists of guidance based on information gathered by ground radars and then uplinked to the missile. ECM is directed at the ground station in this

instance. In either case, breaking lock forces the tracking radar to reacquire the target and regain lock. This forced reacquisition can actually be looked at as reducing the missile's probability of kill (PK), since the missile is in flight but is not receiving guidance while the tracking radar is unlocked.

Infra-red countermeasures (IRCM), such as flares, can be used to defeat missiles with heat seeking guidance. These missiles can launch based on radar acquisition or visual sighting. For any of these conditions, there are varying degrees of counter measures that can be applied and at various points in the mission.

Problem Statement

In general, an aircraft involved with interdiction will try to minimize its exposure to SAM and AAA acquisition radars. Avoidance is practiced by flying low and fast and utilizing some mixture of terrain following and terrain avoidance. What mixture of TF/TA, commanded clearance altitude, ECM, and velocity produces the lowest or consistently lower exposure? Alternatively, given an aircraft utilizing TF/TA, how sensitive is exposure time to changes in command altitude, velocity, or the use of ECM?

This question is being studied at many different levels and locations within DoD with different

permutations or assumptions, requirements, and models. The amount, scope, and quality of information that can be used to provide answers is limited.

HQ USAF/SA is currently involved with work of precisely this nature and is interested in the results of efforts of this type. In addition, there are local organizations involved heavily in programs of their own, specifically the inclusion of ECM effects into previous estimates. In particular, ASD/XR has been examining aircraft exposure to SAM's while flying TF flight paths. XR uses their TERRAIN model to analyze the impact of the above variables on the success of the DI mission. This model, however, does not address ECM or probability of kill of the aircraft.

Objectives

The primary objective of this thesis effort was to modify the TERRAIN model. The expansions that were accomplished are more appropriate acquisition and launch logic, ECM, including jamming and burnthrough, and an evaluation of survivability in terms of probability of kill (PK).

The secondary objective of this effort was to provide the analyst, who must choose from existing methodologies for a study, an idea of the SAM/AAA simulations and analysis tools that exist. In the course of my research,

I completed a survey of the existing SAM/AAA methodology. Particular attention was paid to the differences in features, assumptions, tractability, applicability, and limitations between models. This information has been consolidated into a side-by-side comparison of TERRAIN and six other models. A discussion of the important points of comparison is included as Appendix A. A two-dimensional chart actually comparing the model characteristics is included as Appendix B. These appendices can be used to gain understanding into the availability and relative advantages and disadvantages of a model and may help the analyst or decision maker to determine which of the set of methodologies to apply to his problem. It may also help to reduce the proliferation of SAM and AAA models within the DoD community, since users will perhaps be more aware of currently existing models that could satisfy their requirements.

The tertiary objective of this thesis was to provide a framework for serious analysis of TF, TF/TA, velocity, altitude, and ECM tradeoffs. My work has been kept unclassified, therefore specific results and conclusions are not operationally applicable. Given the relevant data, however, and the required revalidation, the model that has been developed should provide accurate insights.

Significance

Up until now, not much information has been gathered on the specific tradeoff effects surrounding use of TFR. In order to develop sound tactics that will keep aircraft and pilot losses as low as possible, more information is required. As more results are collected and a broader base of experience is built, more effective tactics can be developed.

Scope

The model testing and application examined a generic aircraft by varying its flight parameters. Command altitude varied from 200 foot clearance to 2000 feet. Aircraft velocity varied from Mach .5 (559 fps) to Mach 1.2 (1342 fps). Terrain following and not terrain avoidance was played. Aircraft performance was evaluated at the maximum g level the pilot can tolerate. The flight paths that were flown are representative of those that might actually occur. The threats that were examined are generic and included a radar SAM, an infrared SAM, and an anti-aircraft artillery gun.

II Description of TERRAIN Model

Features

TERRAIN is a FORTRAN IV based analytic model of a tactical aircraft penetrating a SAM and AAA defense array. It is currently operational on the CDC CYBER 74 in overlaid, UPDATE format and requires 70700 octal words of core. The model is currently capable of handling A-10, F-15, F-16, B-1, and Tomahawk penetrators. The defenses that can be modeled are the SA-2 through SA-11 and ZSU 23-4. The digitized terrain data that is incorporated is that of the Fulda Gap region of West Germany, Defense Mapping Agency Sector G81, at 12.5 meter data point separation. Other data bases can be used with only minimal modification of other data files and no hard wire changes.

The defense locations, numbers, and operating characteristics are stored on a disk input file. Aircraft operating characteristics and default values for user options such as aircraft velocity, command altitude, ride roughness, etc., are "hard wired" into the code but can be changed interactively. A user may take horizontal cuts through the terrain to find points at, below, or above a specified altitude. This action indicates the location of the high and low altitude extremes of the terrain within the geographic region. The defensive locations may also

be displayed. These are useful options for planning an ingress/egress route. The user may input a flight path by specifying an initial point, turn points if desired, and a final point. The program then generates the actual altitudes of the flight path from the terrain following options specified. At this point, the user may:

1. Determine what terrain is visible (not masked by other terrain) from a given aircraft position.

2. Plot the terrain altitude cross section which lies under the aircraft's flight path.

3. Plot aircraft altitude and terrain altitude under the flight path as a function of distance flown. Also provided are the minimum and maximum clearance, average clearance, and a measure of the variability of the clearance.

4. Change the aircraft characteristics or adjust flight parameters.

5. Obtain a distribution of the slope of the underlying terrain to see how smooth or rugged it is. A fast Fourier analysis on the terrain is available to highlight the frequency of change of the underlying terrain.

6. Obtain the distribution and Fourier analysis of the slope of the flight path and derive the probability of clobber.

7. Obtain summary graphs of threats the aircraft was

exposed to as a function of time into the mission.

8. Plot the sites that took shots at the aircraft and determine which would have been effective.

9. Plot ADU and target locations as well as roads and international boundaries.

10. Determine which threats can see or be seen by the aircraft at any given time.

11. Plot each threat site's LOS (line-of-sight) region as a function of altitude.

12. Modify the initial beddown of threats and their capabilities and characteristics and produce another flight path.

The twelve options listed above provide the analyst with the means to systematically vary input parameters and examine different forms of output to see how sensitive the model results are to changes in the inputs. For the purposes of my research, the model operation and variable parameterization can be described as follows:

1. Flight path specification.

2. Flying the aircraft with its defined flight parameters over the course specified using a terrain following algorithm to determine the actual altitude profile of the flight path.

3. Calculation of the ADU to aircraft LOS data for the entire flight path.

4. Calculation of launch times, misses, and possible hits.

Note that this four step process requires use of only a few of the twelve options above. These are the sections of the model I require to analyze the validity of the changes to be introduced. These sections will be discussed in detail. The sections that are not discussed should not be dismissed as unimportant. They provide valuable information and tools for analysis. They do not, however, contain methodology which is used in my testing process, and for that reason will not be discussed.

Logic of Incorporated Processes

<u>Flight Path Specification</u>. The flight path specification section reads in X,Y coordinates as initial points, turn points, or end points. Each input pair is checked to see if it exceeds coordinate bounds, or if the change from its last position was so small as to be unuseable. If the point is outside of bounds, it is redefined to the nearest point within bounds. If the point that was input was the endpoint of an undersized leg, the endpoint must be redefined by the user.

Given an acceptable point, the equation of the line representing the last leg is calculated. The leg that was just defined is broken into small increments. The X,Y position of the endpoints of these increments is converted

to an index. This index is used to enter the large array of terrain altitude data. The endpoint's altitude is interpolated from the points closest to it in the array and written to a disk file. This data then provides an altitude profile of the terrain under the flight path which may be plotted (see Appendix C, Option 4).

<u>Generation of TF Flight Path</u>. Once the flight path has been specified and the height of the underlying terrain is known, the plane can be flown over the terrain with the terrain following algorithm to determine the altitude profile of the flight path. First, the flight parameters must be read in from disk and converted as needed. The critical inputs are the PHI, PSI, APHI, and APSI matrices. These matrices contain coefficients that determine how the aircraft transitions between flight states, namely the flight path angle, control surface deflections, velocity, altitude, etc. The PHI and PSI state transition matrices provide coefficients for the instances where the aircraft is attempting to fly a vertical acceleration within the pilot's limits. The APHI and APSI matrices govern the instances where the aircraft is attempting to fly a vertical acceleration outside of limits.

Once the flight parameters have been input, the aircraft can begin its flight. Values for the ride roughness, starting position, velocity, and altitude are

initialized. The aircraft's radar begins sweeping the terrain along the aircraft's velocity vector. The radar has a maximum downlook angle which forces it to look only at terrain it will be approaching and needs to consider, not the areas nearly underneath it which have already been observed and taken into account.

The maximum downlook angle specifies the minimum range for the scan, and the maximum range is given either by the radar's range limitation or lack of terrain data in the model. The beamwidth of the radar is very narrow and centered on the aircraft's velocity vector. The actual terrain that is considered is a line segment extending in front of the aircraft collinear with the aircraft's velocity vector. The DMA terrain data is supplied at 12.5 meter point separation. This forms a two dimensional grid. For ease of understanding, this grid can be pictured as a set of parallel lines overlaid with another set of parallel lines, perpendicular to the first set. Now the line segment representing the flight path scan is placed on the grid. At every point of intersection of grid line and flight path line segment, the terrain altitude is acquired by linear interpolation between the two closest grid line intersections on that grid line. Figure 2-1 illustrates this process.

After all the usable terrain reference points have been obtained in this manner, the TF algorithm checks to

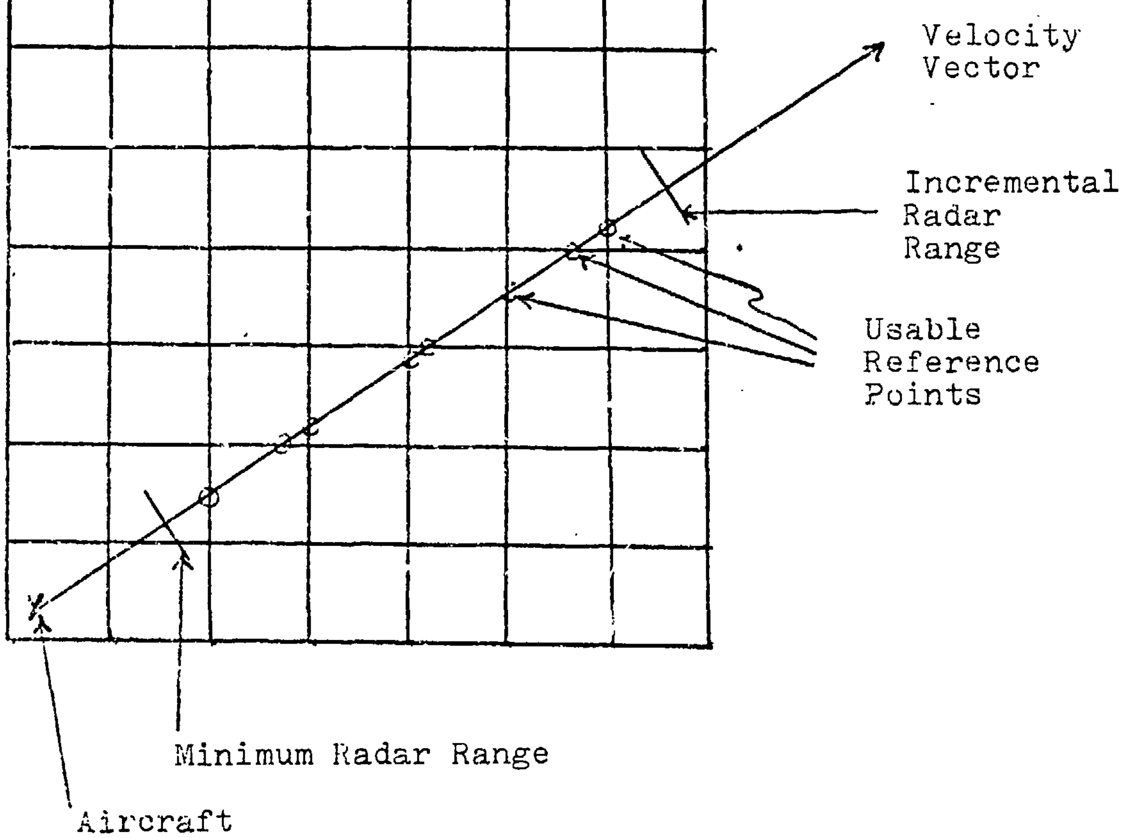

Figure 2-1 TERRAIN Grid and Reference Points

make sure that there were enough points produced from the scan to continue with the algorithm. If an insufficient number of points was generated due to radar noise or weather, the aircraft is forced to gain altitude. Given that there were enough points to consider, the algorithm proceeds to check whether or not each of the points is in line of sight. This is accomplished by calculating the angle between the local horizontal and the LOS line from the aircraft to the terrain reference point. Figure 2-2 shows how the initial first angle is established.

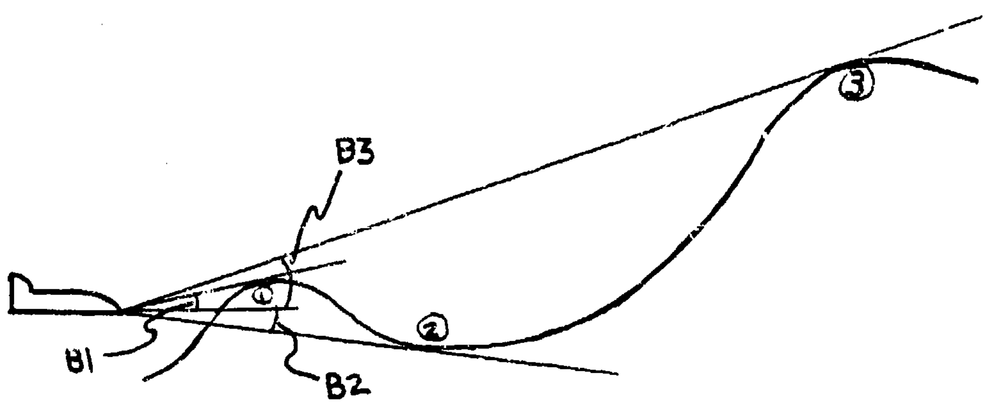

Figure 2-2 Determination of Climb/Dive Angle

B1 is the terrain elevation angle for point 1. This angle (and point) may be eliminated from further consideration if the LOS only grazes the terrain at that point. This check models the fact that the radar return from such a point would be necessarily weak and, therefore, unusable. The actual check is made by comparing the calculated LOS

angle with a minimum grazing angle and throwing the point out if the LOS angle is less than the minimum allowed.

Point 2 is evaluated next, and the angle B2 is determined. Since B2 is less than B1, B2 is not in line of sight and need not be considered by the TF algorithm. The last reference point, point 3, subtends the angle B3. B3 is a larger angle than the current limiting angle B1, so B3 becomes the new limiting angle.

The methodology incorporates a section which produces statistically generated radar noise, and its use in the TF algorithm is controlled by the user with a data switch. The power of the radar from the transmitter and the power of the reflection from the terrain is calculated. The radar power attenuation through the atmosphere is calculated, and, thence, the power of the received echo. If the echo is too weak, the terrain point is thrown out. This process can be carried out using a standard TF radar or a laser system. The choice is controlled by the user with another data switch.

As the radar beam scans up and down, it may pick up backscatter reflection from rain or clouds. The effective backscatter rain area above the target in the center of the beam at the target range is estimated. The radar beam is assumed to penetrate 90% of the way into the rain or clouds. The power attentuation is calculated, and the power of the received echo is calculated. If the weather

reflection signal is stronger than the reflection from the terrain reference point, the aircraft is forced to increase altitude.

The entire angle determination process, as described, is carried out for all the terrain references, and the overall limiting flight path angle is determined. This is the climb angle that the aircraft must fly to avoid the terrain. The required climb angle is converted to guidance commands and required aircraft performance and compared to the aircraft's limitations. The aircraft must then transition from its current state to the next dictated by the required climb angle. This transition will occur in either of two instances; where the required vertical acceleration is within pilot limits, or where it exceeds them. Depending on which instance occurs, the different state transition matrix will be used to affect the aircraft.

The states that are to change during the transitions are:

1. Aircraft velocity.
2. Angle of attack.
3. Pitch angle.
4. Pitch rate.
5. Vertical acceleration.
6. Elevator angle.

7-10. Other aircraft control surfaces.

(NOTE: Aircraft velocity for purposes of updating ground position is a constant. The aircraft velocity state that changes is used to calculate energy height and from that, the feasibility of a maneuver.)

These state variables are listed in a state vector y. The current values are denoted as y_n, and those after the transition as y_{n+1}. The state transitions can be represented in terms of the simple difference equation,

$$\dot{y} = ay + bu \qquad (2\text{-}1)$$

where

$\dot{y}$ represents the changes in the state variables,

y represents the current values of the state variables,

u represents the incremental acceleration of the aircraft, and

a and b are performance coefficients.

Using the definition of the derivative, Equation (2-1) can be expressed as

$$\lim_{\Delta t \to 0} \frac{y_{n+1} - y_n}{\Delta t} = ay_n + bu_n \qquad (2\text{-}2)$$

which is approximated by

$$y_{n+1} = (1 + a\Delta t)y_n + (\Delta t b)u_n \qquad (2\text{-}3)$$

Now $1 + a\Delta t$ has been calculated as the transition matrix PHI (APHI for vertical acceleration out of limits). The Δtb expression has been calculated as the PSI (or APSI) matrix of the control states transition coefficients. This leaves

$$y_{n+1} = \phi_a y_n + \psi_a u_n \qquad (2\text{-}4)$$

The vector y_{n+1} provides the new state variables values for the aircraft after evaluating the current point on the aircraft's flight path. The next and succeeding points on the flight path are evaluated similarly.

Aircraft-ADU LOS Calculation. LOS calculation is a relatively simple process. The flight is examined step by step. At each point, the list of defenses is examined one by one to see if LOS exists. This determination is accomplished by first specifying the X,Y,Z coordinates of the aircraft position and the defense position. Then the equation of the line between the two points in three-space is determined. At every point where the projection of that line onto the X,Y plane intersects the terrain grid, the terrain elevation is interpolated, and the altitude of the three-space line for that X,Y point is calculated. If the terrain altitude is higher than the altitude of the line joining the aircraft position and defense position,

then no LOS exists.

The multipath angle can be taken into account during these calculations by adjusting the height of the aircraft (ZAC) by DH.

$$ZAC = ZAC - \tan(MultiPathAngle) * Range(AC \text{ to } ADU)$$

<u>Calculation of Effective Launch History</u>. The calculation of launches, misses, and potential hits requires initialization by weapon type of the minimum and maximum launch intercept distance, the reaction lock-on time, the length of break time that forces the defense into a reacquisition, the average velocity of the projectile, the guidance type of the projectile, the approaching/receding flag, and the shoot-look-shoot assessment time. The algorithm steps through the flight path time increment by time increment. At each time step, each defensive site is considered. The aircraft location in three-space at the minimum and maximum intercept times is determined, and then the mask status is determined. If the aircraft is masked, the cumulative current break time is incremented and the next defense is checked. If the aircraft is not masked, the velocity vector is checked to determine whether the aircraft is approaching or receding. If the aircraft is traveling in a direction that prevents the ADU from engaging it, the next defense is checked. If

the aircraft is closer than minimum range or outside of maximum range, no launch can occur and the next defense is checked. If the site has exhausted its munitions, the next defense is examined.

At this point in the launch logic, all conditions for a launch have been satisfied. The cumulative effective launch time is incremented by adding the model's delta time variable to the launch time counter. This delta time is added to the counter every time launch conditions are satisfied and no missile from this site is currently in flight (the shoot-look-shoot assessment time has not passed). The number of launches is incremented. After launch, the approximate intercept time is calculated, and if loss of LOS occurs before that time, a miss is recorded (except for IR types).

This process is completed for all sites and all flight path increments. The cumulative values of effective launch time, total launches, number of ineffective launches, and number of (potentially) effective launches can then be provided.

This chapter has described the major algorithms of the TERRAIN model that are required in a vulnerability or survivability analysis: specification of the flight path, generation of the terrain following flight path, calculation of aircraft-ADU line-of-sight, and calculation of the effective launch history. What is needed now are

the modifications which will allow the vulnerability analysis tool (TERRAIN) to be used as a tool in survivability analyses (MODIFIED TERRAIN).

III Development of the MODIFIED TERRAIN Model

Limitations

The TERRAIN model was originally selected to be the primary methodological tool in a survivability analysis. This decision was reached after extensive literature review and interviews with agencies currently involved with SAM research and modeling. TERRAIN's availability was an important factor in my decision, but the fact that it already had many of the capabilities that I required for analysis of the survivability problem weighed heavily. After some work with the model, I realized that there were significant omissions and limitations within the model, and the emphasis of my research shifted from analysis to development.

The first of the important limitations I found with the model was the fact that ECM was not considered. The original purpose of the program was to provide data on aircraft vulnerabilities, not survivability. Vulnerability is the measure of how often or how long the aircraft is subject to hostile fire. Survivability is the measure of the aircraft's probability of not being destroyed, i.e., the probability of surviving.

My work requires the ability to assess survivability and expands the required scope of the model. Insomuch as U.S. armament doctrine relies on technical rather than

numerical superiority, ECM effects constitute a major component of the air-ground battle and are naturally of interest.

The second limitation dealt with the measures of effectivevess that were used. The dependent variables of the model were exposure time and number of effective launches. Nowhere were the probabilities of hit or kill assessed. This arrangement was adequate when the purpose of the mooel was to provide an aggregate number relating to the effectiveness of the TFR. The analyst was provided with an estimate of the percentage of the time the aircraft could be shot down. I required more specific, less aggregate, results. In addition to knowing when an aircraft was out of mask and a SAM site could fire, I needed a measure of the effectiveness of those SAM launches. The single-number measure of effectiveness that was required was the cumulative probability of kill.

The third major limitation identified was the lack of the capability to change flight parameters such as aircraft velocity or command altitude during the generation of the flight path. TERRAIN currently allows only one set of flight parameters for each individual flight path. Omission of the capability to change these parameters at any point in the fight path does not strictly model the actual system and reduces the flexibility of the program and its use to the analyst.

ECM Background

Before proceeding, it may be helpful to briefly review some pertinent ECM terminology and methodology. An air defense unit uses a radar to search for, or to track, enemy aircraft. The site transmits a radar beam at a certain frequency and power. Each radar wave is generated in pulses. These pulses exist for a finite length of time called the pulse width. At the time of transmission, the power, antenna gain (ability of the antenna to concentrate signals), and frequency of the wave are known. The radar then gathers all the incoming signals that have been reflected back to the receiver and analyzes them to determine the azimuth, range, and elevation of the enemy aircraft.

This process sounds simple, but is actually a bit more complicated. First, there is inherent noise within the radar itself, as well as that received from exterior sources. The received signals must be stronger than the surrounding noise, or the radar will disregard the target return. In an effort to reduce the number of false returns, radars require the reflected signal power to be larger than the noise power by some specified ratio, known as the signal-to-noise ratio (SNR).

The radar must also deal with distinguishing a low flying aircraft from ground clutter (terrain and

vegetation). There is a certain distance beyond which the radar cannot make the necessary distinction. This distance is called clutter range and is a function of how finely the radar can resolve targets (the size of the resolution cell), the size of the target (RCS), the radar pulse width, the half-power beamwidth of the radar, the subclutter visibility, and the power of the radar return from the clutter. As with normal radar transmission and reception, there is a cutoff power level for identifying targets or dismissing the return as clutter. The target return must exceed the clutter return by a certain ratio called the signal-to-clutter (S/C) ratio.

The half-power beamwidth mentioned above is the angle measured from the center of the radar beam outward to the point where the power has fallen off by 50%. This central cone of the radar beam illuminates the target. Subclutter visibility is a measure of how reliably the radar can see a target in clutter with a given S/C.

The third problem area the radar encounters is an aircraft that is jamming the radar in an attempt to deny range, azimuth, or elevation information. For a jammer to be effective, the jammer power received by the radar must exceed that of the power received from the signal originally transmitted by the site and bounced off the aircraft. In other words, there is a required jamming-to-signal (J/S) power ratio for the jammer to be

effective. When the jammer is effective, the radar receives less and less reliable position information. Missiles launched under these conditions have less chance of finding and killing their targets. Herein lies the benefit of ECM, namely the degradation of PK. With this brief background in radar and ECM, it will be easier to understand the discussion that follows.

PK Logic

The overall probability that an aircraft will be killed sometime during a mission is a function of the number and effectiveness of the individual shots. Each launch has a probability of kill called PKSS, the single shot probability of kill. The probability that the aircraft is killed depends on the probability that any one, or any number of the single shots killed the aircraft and is expressed as

$$PK = 1 - (1-PKSS_1)(1-PKSS_2)\ldots(1-PKSS_n)$$

or

$$PK = 1 - \prod_{i=1}^{n}(1-PKSS_i). \qquad (3\text{-}1)$$

The expression of the cumulative PK in this form assumes that the individual shots are independent events, and that there is no learning as to aircraft position or velocity

between shots. The next requirement is to derive all the single shot PK values.

Calculation of PK for Missiles

PKSS is calculated based on the dispersion of missed shots about a target. The distribution of missed shots is defined to be circular normal in a plane perpendicular to the LOS between the projectile and the aircraft. The circular normal distribution (Ref 4) is defined as

$$f(x,y) = \frac{1}{2\pi\sigma^2} e^{-R^2/2\sigma^2} \qquad (3\text{-}2)$$

where $R^2 = x^2 + y^2$ (miss distance). In the following, P(A) is defined as the probability that a given shot's miss distance is less than some specified value. Probability is derived from the definition of the distribution by integrating over the area of the miss circle.

$$P(A) = \frac{1}{2\pi\sigma^2} \iint_A e^{\frac{-x^2+y^2}{2\sigma^2}} \, dx \, dy \qquad (3\text{-}3)$$

Transferring to polar coordinates with

$X = r \cos\Theta$ and

$Y = r \sin\Theta$,

$$P(A) = \frac{1}{2\pi\sigma^2}\int_0^R\int_0^{2\pi} e^{-r^2/2} \quad dr\, d\theta \qquad (3-4)$$

$$P(A) = 1 - e^{-R^2/2\sigma^2} \qquad (3-5)$$

CEP (Circular Error Probable) is defined as the range (value of R) that yields a value of .5 for (3-5). That is,

$$P(A) = 1 - e^{-CEP^2/2\sigma^2} = .5 \qquad (3-6)$$

$$e^{-CEP^2/2\sigma^2} = .5 \qquad (3-7)$$

Continuing from equation (3-5) and multiplying the exponent by a form of one,

$$P(A) = 1 - e^{\left[\frac{-R^2}{CEP^2} \cdot \frac{CEP^2}{2\sigma^2}\right]} \qquad (3-8)$$

$$= 1 - e^{\left[\frac{CEP^2}{2\sigma^2}\right] \cdot \left[\frac{R^2}{CEP^2}\right]} \qquad (3-9)$$

Substituting (3-7) into (3-9),

$$P(A) = 1 - .5^{R^2/CEP^2} \qquad (3-10)$$

PKSS is derived from (3-10) by arbitrarily defining the miss distance range for P(A) as the lethal radius (R_L) of

the weapon being used. P(A) is now PKSS, the probability that a single shot will fuze within a close enoug distance to kill the target.

$$PKSS = 1 - .5^{(R_L/CEP)^2} \qquad (3\text{-}11)$$

R_L values have been calculated through experiment and analysis and are available as table look-up values as functions of the aircraft type and missile type. CEP values are calculated differently for the with ECM case ("wet"), and the without-ECM case ("dry").

Missile CEP Values

The form of the dry CEP equation (Refs 19,16) is:

$$CEP = \sqrt{(k_1 * R^6 + k_2 * R^4)/RCS + k_3} \qquad (3\text{-}12)$$

The constants k_1, k_2, and k_3 reflect aggregated values of inherent radar and missile error (Ref 19). The exact form of this equation will vary depending on the missile type. These values account for many error sources (gimbal accuracy, communications lag, turbulence, noise, internal system temperature, computer accuracy, aimpoint lead, fuzing variability, RF frequency, etc.) that are relatively unimportant when considered individually, but when taken together are significant. These values are

aggregated rather than being individually determined, since to do so requires more repetitive calculation and time than is gained in accuracy.

R is the slant range from the aircraft to the defensive site.

RCS is the radar cross section of the aircraft as seen by the defensive site and measures the amount of radar reflective surface in square meters that the aircraft presents. RCS is normally a function of radar frequency, aircraft velocity, and orientation of the aircraft with respect to the defensive site. For my purposes, I have simplified the functional relationship by combining the independent variables and indexing a table of known RCS values by aircraft type and orientation. There are eight orientation angles: looking at the aircraft nose on, 0 degrees, 30 degrees off the nose, 60 degrees off the nose, 80 degrees off the nose, broadside (90 degrees off), 110 degrees off, 150 degrees off, and from the tail (180 degrees off the nose). RCS values on one side of the aircraft are the same as those on the other side, so there is no need to index at more than 180 degrees. RCS for orientation angles between the four data points is provided through linear interpolation.

The form of the wet CEP equation (Refs 19,16) is:

$$CEP = \sqrt{k_1 * R^2 * RJS + k_2 * RJS + k_3} \qquad (3\text{-}13)$$

k_1, k_2, k_3, and R are identical to the dry parameters. RJS is the ratio of the aircraft's jamming power to the power of the radiated signal from the defensive site at a point in space. RJS (Ref 4:101) is defined as

$$RJS = 4\pi R^2 * ERPJ/(RCS * ERPR) \qquad (3\text{-}14)$$

where R and RCS are as before, and ERPJ and ERPR represent the effective radiated power of the aircraft (jammer) and the defense (radar), respectively.

At this point then CEP, and therefore PKSS and eventually PK, can be calculated for all cases. There is one further breakdown of the ECM case to consider, however, and that is the area of radar acquisition.

Effects of E[illegible]

In its original form, TERRAIN tested only for line of sight acquisition (mask/unmask) and presence in the intercept envelope. When considering ECM, there are three additional quantities to consider: clutter range, self-scree[illegible] r[illegible], and detection range. Clutter range (R_C), is the range beyond which the radar cannot distinguish clutter from a target. Self-screening range (R_{SS}) is the di[illegible]ance beyond which the aircraft has the ECM power to conceal itself from the defensive radar. The point at which the aircraft's power is insufficient to

point at which the aircraft's power is insufficient to screen it from the defensive radar is called the burnthrough point. R_{SS} is a function of RCS, ERPR, ERPJ, and required J/S ratio.

Detection range (R_D) is the maximum range at which a threat radar can see an aircraft. R_D is a function of the radar power and the RCS of the penetrator.

MODIFIED TERRAIN evaluates these three new range values and the maximum firing range used in the original detection logic and chooses the smallest of these values as the limiting range. Penetrators beyond this limiting range are not susceptible to SAM fire, therefore, PKSS values are not evaluated.

These range limitations cover only the case where the defense uses a radar type misile. Changes to evaluate infrared missiles and AAA were also incorporated. Calculating PKSS values for infrared type missiles is done in a manner similar to the radar type missile calculations. The requirement for firing an IR missile is that the target must be within IR lock-on range. Lock-on range is a function of the aspect angle of the target to the SAM. A table of lock on ranges obtained through observation and intelligence reports provides the data for key orientations. The table is indexed by aspect angle, aircraft type, and weapon type. If the aircraft's slant range is greater than the missile's lock-on range, no

launch occurs. Otherwise, a launch occurs and a CEP is assigned, depending on weapon type. CEP for IR type missiles is assumed to be relatively invariant and not functionally dependent on any aircraft or missile flight parameters. Once the CEP is known and the lethal radius looked up as before, a PKSS is calculated.

Calculation of PK for AAA

Calculating PKSS for a shot from an anti-aircraft artillery tube is greatly different than the procedure for SAM's. For AAA (Refs 10:38, 15),

$$PKSS = \frac{A}{A + 2\pi\sigma} \, e^{-B^2/A+2\pi\sigma} \qquad (3\text{-}15)$$

where

A = average vulnerable area of the aircraft,

$\sigma = (k_4 * R)^2 + (k_5 * R)^2$

$B = .5 * g * T^2 * INC$ (aiming bias) (3-16)

$T = R/(V - D*R)$ projectile time of flight,

and

k_4 is the system error in mils,

k_5 is the ballistic error in mils,

g is the acceleration due to gravity,

INC is the incremental vertical acceleration of the aircraft,

V is the muzzle velocity of the projectile (m/s),

D is the ballistic drag coefficient (1/sec).

For the optimistic case where aiming bias (3-16) is zero (INC is relatively small and constant), the exponent portion of the second half of (3-15) is zero, and the entire second half of the equation goes to one, resulting in

$$PKSS = \frac{A}{A + 2\pi\sigma} \qquad \text{(Ref 17)} \qquad (3\text{-}17)$$

PKSS values for a AAA round are generally very small. AAA is not fired in single shots, however, but in bursts. Burst sizes are typically 12-24 rounds. To calculate PK from a burst,

$$PK = 1 - (1 - PKSS)^{n} \qquad (3\text{-}18)$$

where n is the size of the burst.

Reliability and Operational Factors

Up to this point, the SAM and AAA sites have been able to fire with 100 per cent reliability. There has been no consideration of a unit in motion not being able to fire, the site operator asleep at the console, or equipment malfunction. The probability of a weapon

failing to operate as designed is known as reliability. The instances where tactics, strategy, human error, or logistical problems affect fire are known as operational factors and presented as a probability (of missed fire). Ops factors (OF) and reliabilities (REL) are provided through intelligence and observation. These values are indexed by weapon types. PKSS is now calculated as the value previously described times OF times REL,

PKSS = PKSS*OF*REL.

Calculation of PKSS in this manner reflects more accurately the realities of an operational environment.

Summary

The original TERRAIN model now effectively no longer exists for the purposes of this study. The original model and the modifications presented in this chapter have been combined to form the new model, MODIFIED TERRAIN.

IV Effects of Selected Model Parameters on PK

The materials in Chapter II described the incorporated processes and logic of the TERRAIN model. Chapter III discussed the limitations of the model and the modifications required to correct those limitations. Before investigating aircraft probability of kill sensitivity, a systematic series of tests needs to be designed. This design requires identification of the variables which influence the measure of effectiveness, namely probability of kill.

The variables in question can be grouped into three sets: terrain following flight path profile parameters, Air Defense Unit parameters, and ECM considerations. The material of this chapter will identify the particular parameters that effect PK, the bounds on the parameters, the significance of the parameters, problems that certain values of the parameters could produce, and methodological or operational ways to fix or avoid those problems.

Terrain Following Flight Path Profile Parameters

Radar Downlook Angle. The radar downlook angle is the maximum angle which the aircraft radar can scan downward. The angle is measured downward from the aircraft's roll axis. The downlook angle can represent a physical limitation on the aircraft radar's ability to

scan, or a limitation imposed on the radar for the sake of efficiency. At low altitudes, the value of this parameter is not critical. A moderately low angle can usually still allow the aircraft to see the terrain to which the flight path must conform. At higher altitudes, however, the downlook angle must be increased to give the aircraft radar a view of immediately underlying terrain. If the commanded clearance altitude for the TF algorithm is great enough and the downlook angle is small enough, the radar will never see the ground and will have no information with which to generate aircraft guidance commands.

Minimum Radar Range. The minimum radar range is the distance in front of the aircraft at which the aircraft radar starts scaning for terrain points to which to conform the flight path. Definition of minimum radar range is dependent on aircraft velocity and commanded clearance altitude. When the aircraft flies lower, the range must decrease. If not, the aircraft may be flown into the ground because the radar has been set too far out and ignores the mountain immediately in front of it. As the aircraft flies slower, so too must the minimum radar range decrease. If not, the aircraft may again fly into the ground. The radar will look out to its minimum range, evaluate the terrain, generate guidance commands, and attempt to maneuver over the terrain.

Figures 4-1 and 4-2 illustrate what happens when the

aircraft flies too low or with a minimum radar range that is too large. In Figure 4-1 the aircraft begins dipping toward peaks too soon, or climbing away from valleys too soon. The velocity should be increased slightly, or the minimum radar range should be decreased slightly. In Figure 4-2 the aircraft is actually hitting the ground and attempting to fly through the terrain. The problems encountered in Figure 4-1 have been pushed to an extreme. The velocity needs a large increase, or the minimum radar range needs a large decrease.

At slower velocities, two problems can occur. First, the aircraft is not as maneuverable and does not respond quick enough to changes in command guidance. Second, and more probable, the aircraft continues flying, the radar keeps scanning, guidance commands are generated, and the aircraft changes its climb or dive angle. The problem here is that the aircraft has not been flying fast enough to actually arrive over the terrain for which the guidance commands were generated many cycles ago. The aircraft must fly faster or the minimum radar range must be decreased.

The radar's minimum look distance can range from several hundred feet to several thousand, again dependent on commanded clearance and aircraft velocity. At altitude, the minimum look distance can be increased since too much importance placed on close-in terrain will

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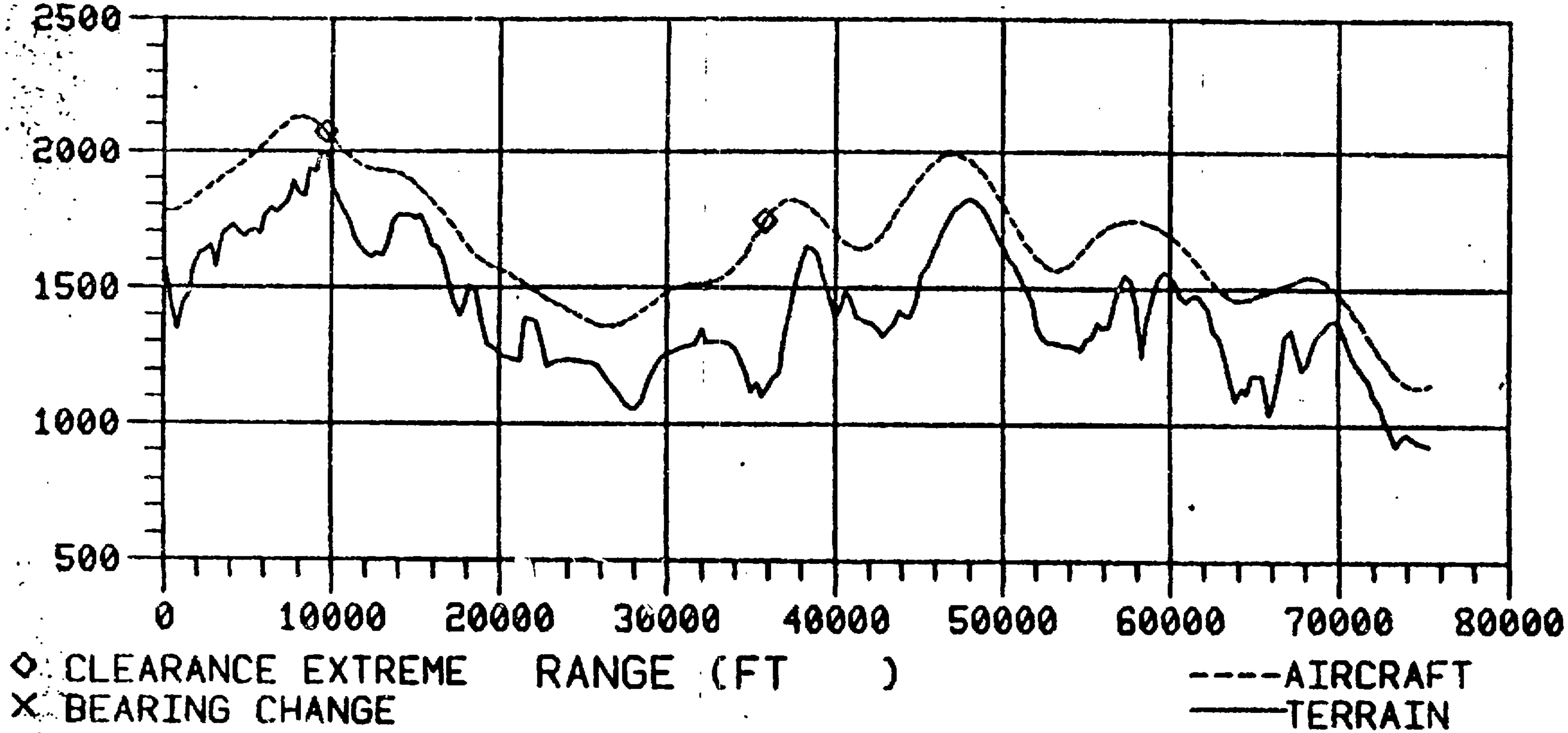
G-81 FULDA GAP TERRAIN UTM(70750,5050)-SU CORNER-10DE,50D36'N 6AUG80
2000



C1	= 1.300	VAC	= 844.0	SIGR	= .3060E-05	ADBPNM	= .2000E-04	D	= .3281
C2	= 1.740	STAT	=0.	F	= 4.000	RDBPNM	= .6000	TN	= .5000
C3	= 1.100	RNCL	= 5000.	BW	= .1396	STEPS	= 1.000	PRF	= .4000E+05
C4	=-.7700	TI	= .2500	RLOS	= 10.00	PRINTMTX	= 1.000	ACMIN	=-.8000
HO	= 200.0	XKGM	= .5000E-02	GDFT	= 2.000	RLM	=0.	ACMAX	= 1.500
RINC	= .1500E+05	TS	= .2500	XLAM	= .5743E-01	PAU	= 15.00	BD	= .2500E-03
RMIN	= 3000.	FT	= .3000E+05	CKT	= .4000E-20	TAU	= .3400E-06	ALPHAR	= .3048E-02
TP	= 2.250	PW	= .2000E-06	BWIF	= .2000E+07	ALPHA	= .4572E-03	RHOR	=0.
GMCL	= .3490	G	= 354.8	RIDE	= 1.000	TSYS	= .1000	GMDL	=-.5236
BMAX	= 1.500	SIGG	= .1000	BIAS	= .2000E-02	RHO	= .1000	DATS0	=0.

RIDE:HARD, MEAN= 249.9, STDEV= 97.3, MIN/MAX CLEAR= 82.3/ 620.6

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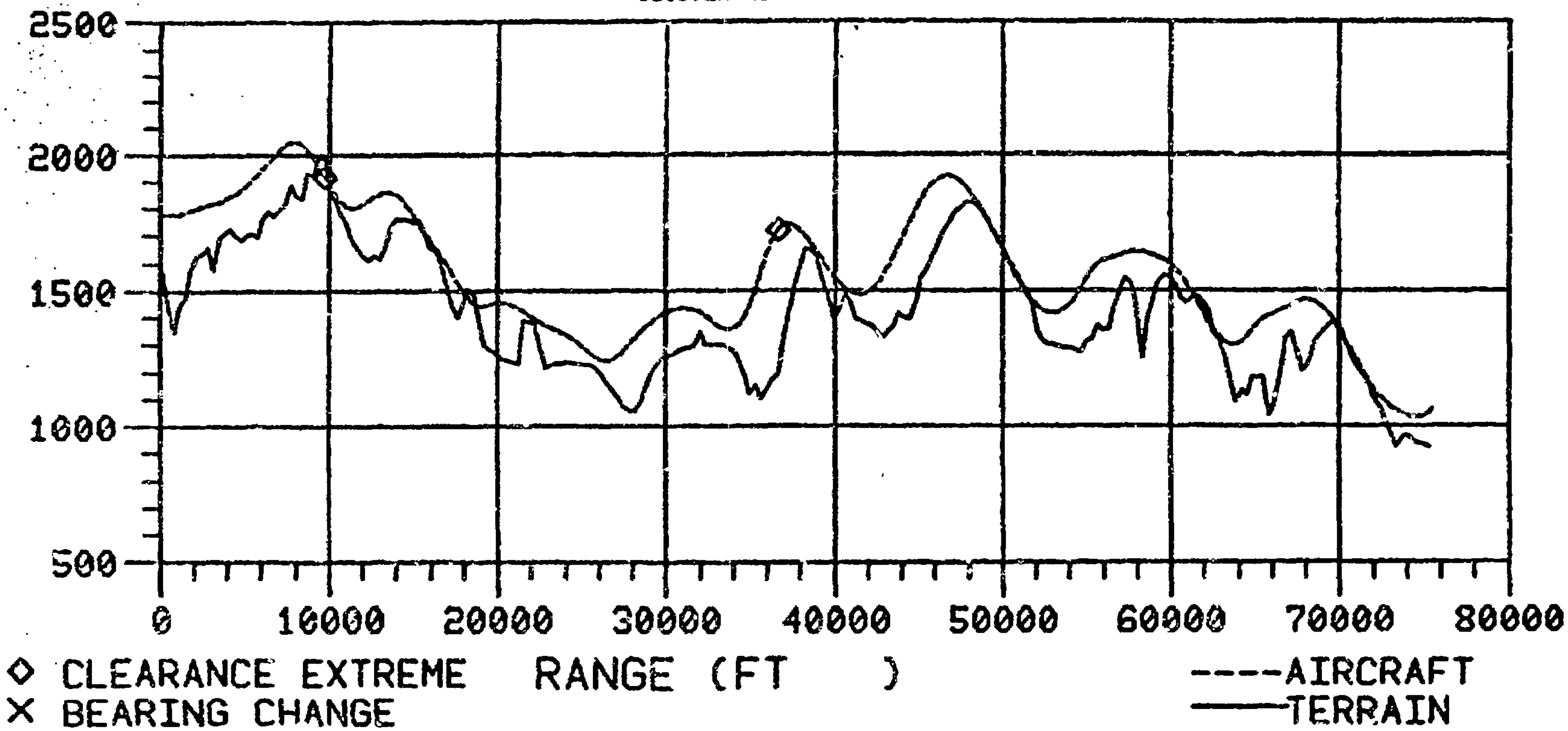
G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
CLOBBER RUNS



C1	= 1.300	VAC	= 559.0	SIGR	= .3060E-05	ADBPNM	= .2000E-04	D	= .3281
C2	= 1.740	STAT	=0.	F	= 4.000	RDBPNM	= .6000	TN	= .5000
C3	= 1.100	RNCL	= 5600.	BW	= .1396	STEPS	= 1.000	PRF	= .4000E+05
C4	=-.7700	TI	= .2500	RLOS	= 10.00	PRINTMTX	= 1.000	ACMIN	=-.8000
HO	= 200.0	XKGM	= .5000E-02	GDPT	= 2.000	RLM	=0.	ACMAX	= 1.500
RINC	= .1500E+05	TS	= .2500	XLAM	= .5743E-01	PAU	= 15.00	BD	= .2500E-03
RMIN	= 3000.	PT	= .3000E+05	CKT	= .4000E-20	TAU	= .3400E-06	ALPHAR	= .3048E-02
TP	= 2.250	PW	= .2000E-06	BWIF	= .2000E+07	ALPHA	= .4572E-03	RHOR	=0.
GMCL	= .3490	G	= 354.8	RIDE	= 1.000	TSYS	= .1000	GMDL	=-.5236
BMAX	= 1.500	SIGG	= .1000	BIAS	= .2000E-02	RHO	= .1000	DAT50	=0.

RIDE:HARD, MEAN= 138.9, STDEV= 108.1, MIN/MAX CLEAR= -71.9/ 526.7

produce a profile which is too responsive to the underlying terrain. The flight path profile at altitude should ideally be much smoother. Conversely then, as altitude decreases, so too should the minimum look distance. Care must be taken not to specify a minimum look distance that would require the radar to scan past its limits (maximum radar downlook angle).

Incremental Radar Range. The incremental radar range is that distance past the minimum radar range which the radar will scan. This distance must be far enough out to take notice of upcoming terrain changes, but not so far out as to cause a flight attitude change 40 kilometers prior to encountering the terrain feature. Specification of the incremental radar range in conjunction with the minimum radar range defines the radar footprint of the aircraft. Looking at the two ranges in terms of the footprint makes it easier to see the problem at a glance. Footprint size and placement are the critical concerns. The footprint must be big enough to see all pertinent terrain features and must be placed at the correct distances to take into account the aircraft velocity.

Commanded Clearance Altitude. The commanded clearance altitude is the vertical separation distance that the pilot wants to maintain between the aircraft and the ground. Maintaining a constant clearance when close to the ground will generally reduce the PK since ADU's

cannot see the aircraft as soon nor for as long. One of the problems encountered at low altitude is the inability of the aircraft to change attitude and direction quickly enough to stay conformed to the underlying terrain at exactly the commanded clearance. The aircraft may overshoot a mountain peak and take a long time to recover, or clobber (fly into the ground). The situation could occur that an aircraft at a commanded clearance of 50 feet could have a higher average clearance, a higher maximum altitude, a longer exposure time, and perhaps a higher PK than an aircraft at 100 feet clearance. Commanded clearance altitudes will typically range from fifty to several hundred feet.

Aircraft Velocity. The speed at which the aircraft travels is a major determinant of PK. In a situation where terrain and clutter are not considered, the faster the aircraft travels, the harder it is for weapons, especially AAA guns, to hit it. Velocity interacts directly and importantly with clearance altitude. At low altitudes, velocity changes affect primarily the altitude profile of the flight path. When velocity is relatively low, the aircraft has time to conform to the terrain and does so efficiently. As velocity increases, the number and magnitude of overshoots increaes, also increasing PK. At higher altitudes, the PK values increase, primarily due to the fact that the ADU's see the aircraft sooner and get

to shoot at it longer. There are advantages to flying at either slow or fast velocities. When velocity is increased, the aircraft leaves the engagement region sooner and the number and effectiveness of shots are decre ed. When velocity is decreased, the aircraft stays awa from the ADU's center of fire longer and can hug the rain closer.

<u>Maximum Sustainable g Forces</u>. The maximum positive and negative vertical accelerations that the pilot and airframe can sustain are the determinants of how accurately the terrain following algorithm can maintain the commanded clearance altitude. As the amount of vertical acceleration that is allowed increases, the ride becomes rougher, and the aircraft becomes more responsive to changes in the underlying terrain. As the responsiveness of the aircraft improves, overshoots (exposure time) and PK decrease.

<u>Underlying Terrain</u>. The terrain that lies under any given flight path is a random variable. One given flight path can have very smooth terrain, which produces a smooth flight path with few overshoots and altitude extremes, but also with little available terrain masking. Another flight path can be moderately or extrememly mountainous. Flight path profiles over terrain such as this will have overshoots of varying degrees but will also provide masking. The point to be noted is that identical aircraft

with identical flight parameters (velocity, clearance, etc.) but different flight paths will have different flight path profiles and therefore different exposure time patterns and PK.

Figure 4-3 presents the flight path profiles for two different flight paths flown with the same velocity (844 fps), clearance altitude (200 ft), and radar footprint. Note the difference in magnitudes of the clearance extremes (designated by diamonds on the profile paths). The mean, minimum, and maximum clearances for the top profile are 236, 64, and 678 feet. The corresponding values for the bottom profile are 309, 189, and 615. There is a difference of 70 feet in mean clearances caused only by a change of terrain. Differences of this magnitude will cause the exposure times to differ comparably.

Air Defense Unit Parameters

Beddown. ADU beddown is a description of the number of ADU sites that are deployed, how many of each type exist, and their geographic locations. The number of sites should logically be chosen to represent some actual or anticipated threat array. It also follows that, as the number of sites increases, the number of shots that will be taken increases and so then will PK. It is important to analyze a situation that is realistic in numbers and

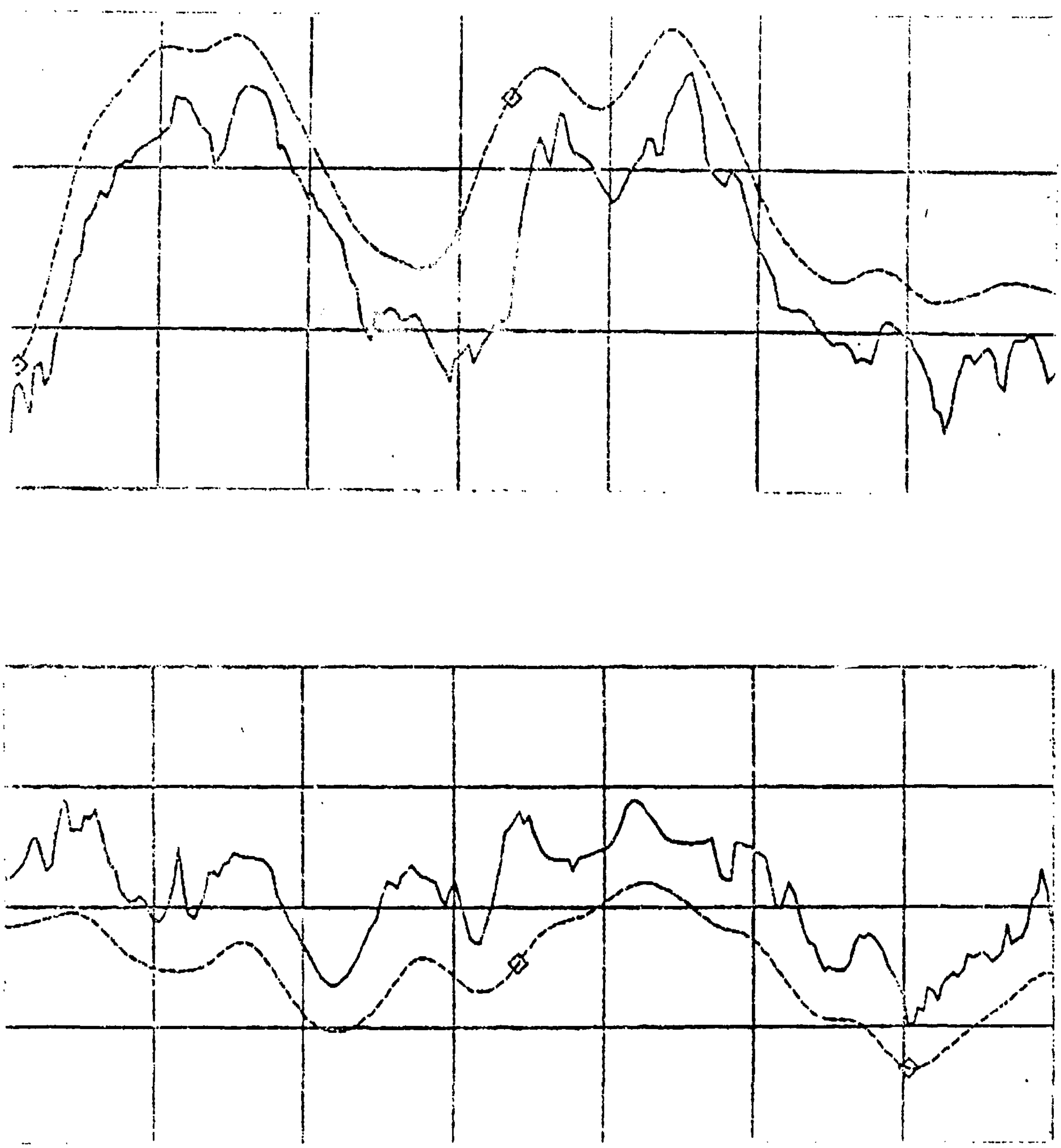


Figure 4-3 Compared Profiles - Different Flight Paths

locations. Figure 4-4 presents a sample beddown.

Beddown and flight path selection work together to determine PK. Beddown can also be viewed as a random variate. Sites may be placed in any number of positions relative to other sites and terrain. For the two aircraft cases (mountainous and smooth) mentioned in the discussion of underlying terrain, the beddown must necessarily be different. The LOS history will also differ between the two cases. Beddown and flight path selection interact to change the LOS history. They can also interact in such a manner as to produce exposure histories and PK values that may overwhelm the expected effects from changes in velocity or footprint.

Firing Doctrine. Firing doctrine specifies how any given site will fire at an incoming aircraft. In the shoot-look-shoot mode of fire, the ADU will fire a weapon, then wait until intercept or expiration of the weapon to evaluate its performance. The site will then gain information on aircraft velocity, altitude, or evasive maneuvering tactics in order to improve the PKSS of the succeeding shots. In the continuous mode of fire, the site does not evaluate the success of previous shots. As the name implies, firing is continuous as long as the aircraft remains in range. This method of firing may be inefficient, since no learning occurs between shots. Shots following a shot with high PKSS may be unnecessary,

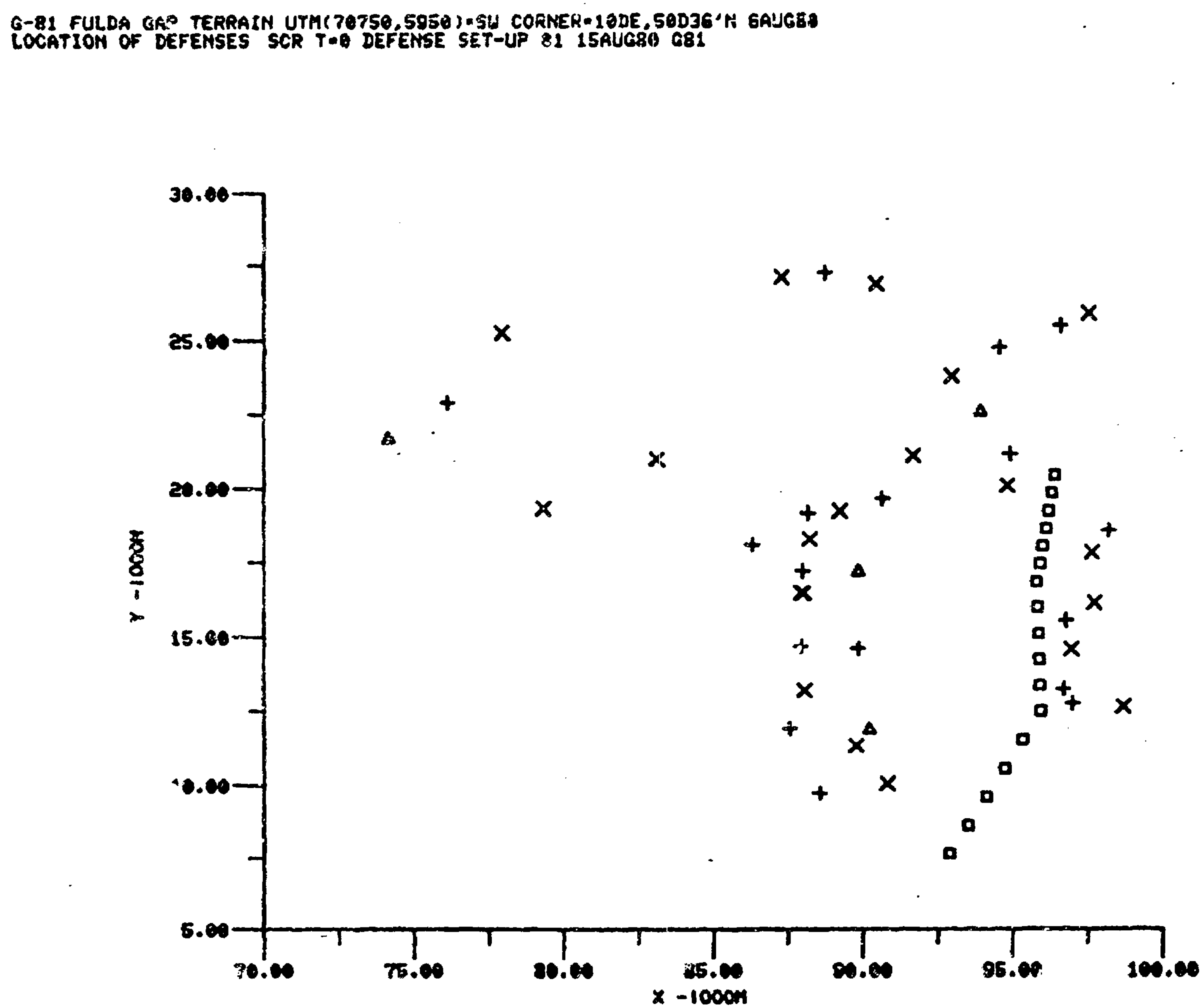


Figure 4-4 Sample Beddown

better used at a later time. The shoot-look-shoot doctrine may also be inefficient, since the longer wait time between shots reduces the number of shots that are taken and, therefore, the PK. While one missile is en route to the target, the second missile may not fire. In the time that it takes to evaluate the first missile's effectiveness, the aircraft may leave the ADU's engagement envelope, and the second shot (which might have been the very effective shot that would have downed the aircraft) never gets fired.

<u>Shoot-Look-Shoot Assess Time</u>. The time that a missile requires to intercept its target plus the amount of time that the ADU requires to evaluate the success of the previous shot and apply information from that shot to the launch parameters of the succeeding shot is called the shoot-look-shoot assess time. In the instances where the shoot-look-shoot assess time is small and the missile time of flight is small, the firing doctrine employed by the ADU approaches that of the continuous mode. As the assess time increases, site efficiency decreases since second and succeeding shots may never occur.

Shoot-look-shoot assess time estimates reflect the perception we have of enemy ADU capabilities. These estimates are available for and applied primarily to radar and IR missile types. Incorrect or unrealistic estimates can severely distort PK values, but that is also dependent

on beddown, flight path, and other parameters.

Reload Time. In the case of continuous fire, the factor that limits the rate of fire is the time it takes to reload a gun tube or switch fire controls to another rail or TEL. As reload time increases, fewer total shots can be fired, and the PK is not as high as it might have been.

Reaction Time. Reaction time is the time that an ADU requires between initial target acquisition and the first fire. This time includes system warm-up, tracking, target identification and confirmation, and loading. If the reaction time for a site is high, the aircraft has a grace period where it is not subject to fire from that site. For an aircraft traveling at high velocity, a moderately long reaction time may be all that is needed to totally negate the effectiveness of the site. Varying the reaction time effects the start fire time, subsequent shots, and therefore the PK.

Reacquisition Time. Reacquisition time is the length of time that it takes a site to regain track after a loss of LOS due to masking. Again, for an aircraft with a relatively high velocity, a moderately long reacquisition time could virtually negate the ADU's effectiveness. If reacquisition time is small, the situation becomes one in which a break lock or loss of LOS does no more than reduce the exposure time. Available launch time is not affected

by any more than the loss of exposure time.

Break Time. Break time is the length of time which must pass after an aircraft becomes masked (ADU has no LOS to the aircraft) before breaklock is declared. The site has lost track of the aircraft and must search for and reacquire it. Projectiles in flight when break lock occurs go ballistic and contribute nothing to PK. For projectiles in flight when LOS is lost but break time has not yet been reached, the aircraft flight path is extrapolated from the last known position and velocity and the projectile can contribute to PK.

PK will also increase as required time to break lock increases, since fewer breaks will occur and more projectile PKSS values count towards PK. Conversely, as required break time decreases and the break-locks occur more frequently, PK will decrease. In situations like this, reacquisition time also becomes a sensitive parameter.

IR Lock-On Range. IR lock-on range is the distance from an IR site at which the IR seeker head can lock onto a heat source and track it. This lock-on range is a function of the IR signature of the aircraft (and so also its aspect angle to the ADU) and the capabilities of the seeker head. This range is sensitive to weather, modifications to the IR signature of the aircraft, and IRCM.

Firing Limits. Each ADU has a minimum and maximum weapon range. If an aircraft is within the minimum range, the missile either does not have quick enough reaction time to track the target or enough time of flight to arm itself. Some AAA have physical limits on their slew rate and cannot move fast enough to fire at the target. The maximum weapon range is primarily defined as the point where the projectile loses propulsion or velocity and falls ballistically. This is the distance beyond which a successful shot simply cannot occur.

ADU Smartness. Smartness is a measure of how aware an ADU is of where its most effective shots will occur; where its lethal envelope is. A smart defense may withhold fire, even though the target is well within the maximum firing range, in the hopes that not as many missiles or rounds will have to be used in order to achieve the same PK. Smartness encompasses the ADU's command, control, and communications systems, radar netting, fire control, and knowledge of the attacking threat capabilities and tactics.

NATO gives the WP countries credit for a given level of smartness. The level that is assumed may or may not be correct. The assumed level is, therefore, a sensitive parameter in a survivability analyis. Will the ADU's fire at first opportunity? Will they wait for a shot x meters into the lethal envelope? Will the site operators even

recognize an incoming target, and will a launch even occur? These are questions which must be answered. The answers to the questions determine how WP tactics will be modeled and will, therefore, affect PK values.

Munition Limits. There is a certain limit on the number of missiles or AAA rounds that an ADU will have. NATO intelligence provides estimates on the number of usable rails, TEL's, and reloads by ADU type. These estimates directly affect the number of shots that will be taken and, therefore, the PK values. Munition limits and firing doctrine are very much interdependent. If a site is firing continuously, it will obviously be limited by the number of missiles on site. When those are exhausted, firing will cease, and that site will no longer be a threat. If a site begins firing at maximum range, it could expend all its available munitions before the aircraft ever reaches the lethal envelope. All the expended munitions have virtually no contribution to PK in that case. There is interaction between munition limits, firing ranges, ADU smartness, firing doctrine, and delay times. With this number of variables having input on the outcome, it is difficult to predict or explain the PK trends.

Salvo Size. AAA sites commonly fire from 12 to 24 shots in a burst. This is the salvo size. The size of the salvo determines the PK of the burst. The bigger the

salvo, the faster is the drawdown of the available munitions at a site. There are tradeoffs among withholding fire to achieve higher PK values later and conserve munitions, using smaller salvos to conserve munitions but achieving smaller PK values, and loading the guns with big salvos and increasing the PK values but running out of munitions sooner.

Use of Elec ronic Counter Measures

Effects on Detection Range. When ECM is used, the range at which an acquisition radar will first detect an aircraft is much less. In other words, ECM degrades the effectiveness of the radar so the ADU will not see the aircraft until it is much closer to the site. When this occurs, the firing opportunities are decreased and, therefore the total PK decreases.

Effects on Missile CEP. When ECM is used, the accuracy of the missile guidance radar is degraded. As the performance of the radar deteriorates, the CEP of the missile deteriorates. It is desirable then, from the pilot's point of view, to have an efficient ECM pod on his aircraft. The efficiency of the ECM is determined by the distance between the jammer and the source and the power of each of the radars.

Aircraft Vulnerable Area

The final parameter that affects the success of the aircraft's mission and its survivability is the average vulnerable area presented by the aircraft. Vulnerable areas are those portions of the aircraft that, if struck by a SAM or artillery shell fragment, would kill the aircraft or at least prevent it from accomplishing its mission. Average vulnerable area can be specified as an aggregate number for the entire aircraft or detailed by critical components.

As the average vulnerable area of an aircraft is decreased, the chance of sustaining a hit that could damage or kill the aircraft is decreased. This forces the ADU to improve its accuracy if the same PK is to be obtained.

Summary

These then are the parameters that influence exposure time, shot opportunities, and PK. The format in which these parameters were presented was identification, definition, significance, interrelationships with other parameters, parameter range, potential problem areas, or anomalous results which could be caused by the parameter, and possible ways to prevent, fix, or explain the anomalies. As is seen with many of the parameters dealing with earliest shot opportunities, defensive smartness, and

doctrine, the interaction among these parameters can be quite complex. Explanations for and understanding of the interactions can only be gained by detailed study of those particular interactions when they occur.

V Model Verification and Validation

Introduction

In any modeling exercise, testing the results for analytic verity and real world validity are the two most difficult and amorphous requirements. Verification is the process of assuring that the variables which require computation are calculated correctly. Verification is difficult because there are often complex relationships within a model that can influence a variable; and analyzing the degree of influence of each of these relationships is involved. Validation is the process of assuring that the results of the model accurately reflect the reality that has been abstracted. Validation is an amorphous process because the analyst cannot know if all the pertinent factors from the real world system of interest have been included in the model or if they have been included correctly. Another significant difficulty encountered in the validation process is finding data from the real world against which to compare the results of the model. Flying aircraft against live SAM and AAA threats to gain comparative data is a prohibitively expensive process in terms of men and money.

This chapter describes the verification and validation process as applied to the MODIFIED TERRAIN model. Of particular concern is the fact that, as alluded

to above, there are few real world observations of modern aircraft penetrating enemy SAM and AAA arrays. In that light, the PK values that are discussed here are relative to each other across different parametric runs and are not anchored with respect to any set of currently validated and accepted benchmark PK values.

The method of presentation of results for verification and validation will be chronological and will follow the test and development history of the model.

Preliminary Tests

After the original development and coding was implemented, a design to comprehensively vary the aircraft velocity and commanded clearance altitude over several different fight paths, with and without use of ECM, was constructed. The purpose of this initial set of runs was: to insure that the model worked with the newly incorporated changes, to check that the results that were observed were in the expected ranges (aggregate verification), and to determine what ranges of velocities and altitudes would be appropriate for the sensitivity runs. The results of these initial runs did work, and the values were in the expected range (i.e., the probabilities were between 0 and 1). Most of the sets of results for the different flight paths produced intuitively acceptable results. When commanded clearance altitude increased, so

did PK. When velocity increased, PK decreased. Figure 5-1 illustrates this case. There were, however, a large number of cases where observed results were counter-intuitive. For example, PK might increase as clearance altitude increased from 200 feet to 1000 feet, but it would dip down when clearance increased above 2000. Figure 5-2 illustrates this possibility.

The most likely cause for the counter-intuitive behavior of the PK curves was incorrect modeling of the detection and launch process. Accordingly, the detection and launch logic within the model was revamped. The sequence of range checks, break-lock tests, and decisions to fire was reorganized. The same set of test runs was resubmitted, and the results were virtually the same with the counter-intuitive behavior extended to the cases without ECM as well. This indicated that the pathology was not a function of ECM use or the order in which certain launch criteria were evaluated, but was a function of some missing relationship in the method for calculating the PK. The missing relationship was hypothesized to be a function of when an ADU began firing, how fast it was firing, and how long it took to run out of munitions. These three factors can be combined and examined as the ADU's choice of firing strategy and how effective that strategy and the shots fired under it are.

It seemed that shots being taken by the air defense

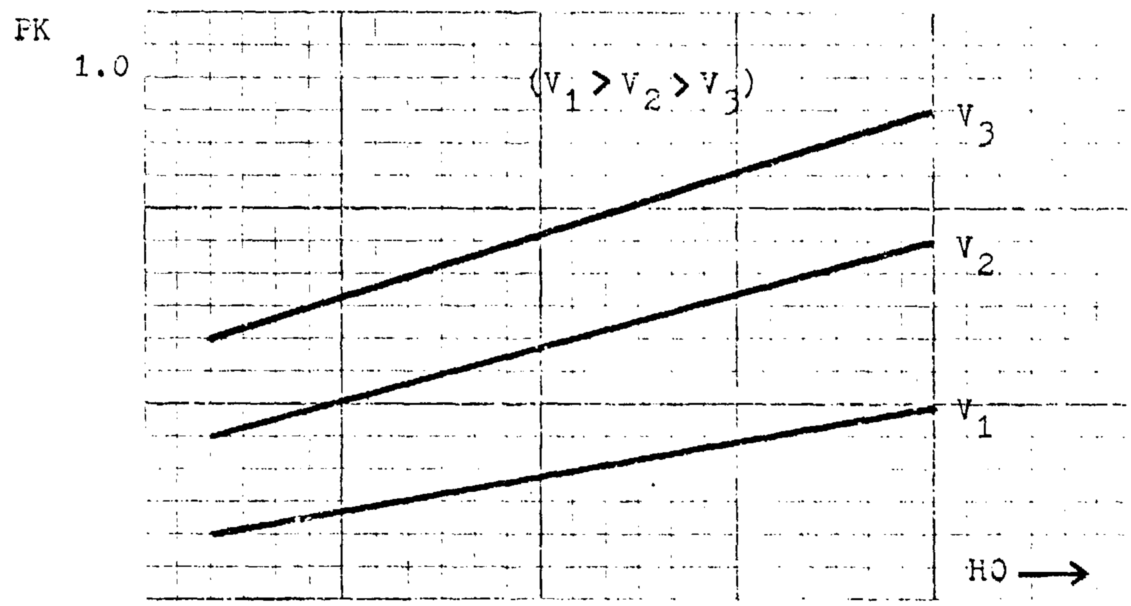


Figure 5-1 Sample Expected PK Curve

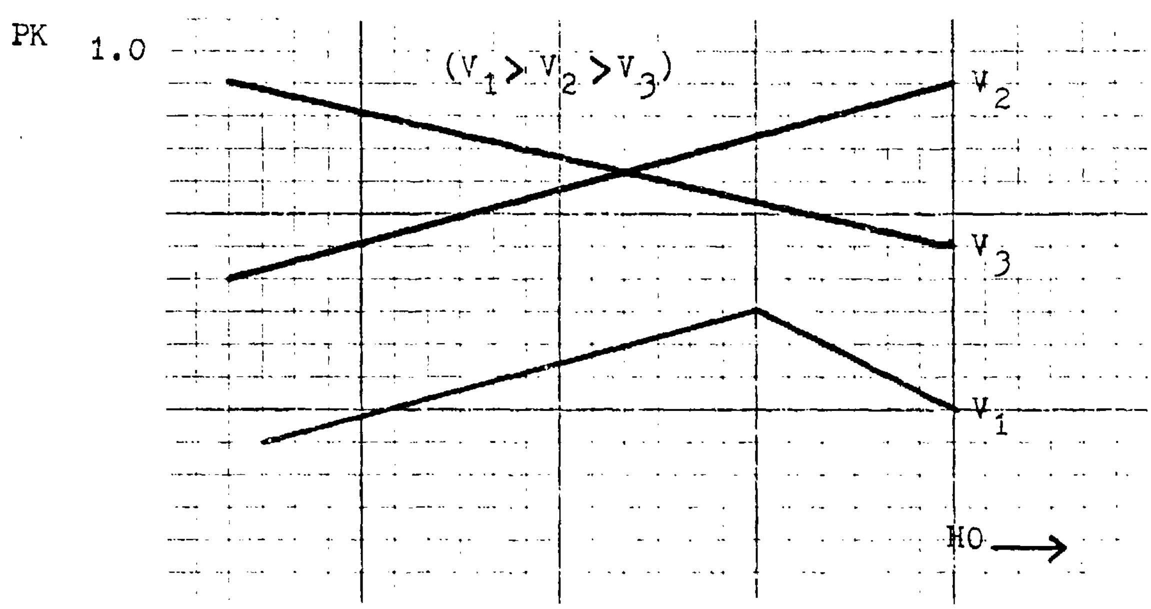


Figure 5-2 Sample Counter-Intuitive PK Curve

units were not as effective as would have been expected. Figure 5-3 displays the PK curves from one of the runs that produced counter-intuitive results. Notice how the probability of kill decreases between 1000 and 2000 feet. One would expect to see an increase in PK as the aircraft flies higher and is exposed earlier and for longer periods of time. PK is not affected solely by exposure time and number of shots; the range at which the shots occur is a strong determinant of PK (primarily in the case of AAA). The effectiveness of a shot is an inverse function of range. The closer a shot occurs, the more effective it will be. The farther away the intercept, the less effective will be the shot. Since the effectiveness of the shots was lower than expected, this implies that too many of the shots were being taken at distant aircraft. The ADUs were firing at too distant a range to have any great effectiveness. In addition, given that the initial firing range was too great, the ADUs might have been firing too fast so that all munitions were expended before the aircraft had an opportunity to progress into the more lethal regions of the ADUs' engagement envelopes.

It seems that there is an important tradeoff to be considered. The increase in altitude will unmask the aircraft sooner and for a longer period of time, allowing more shots to be taken. As has been noted, as the number of shots increases, PK increases. The earlier unmask also

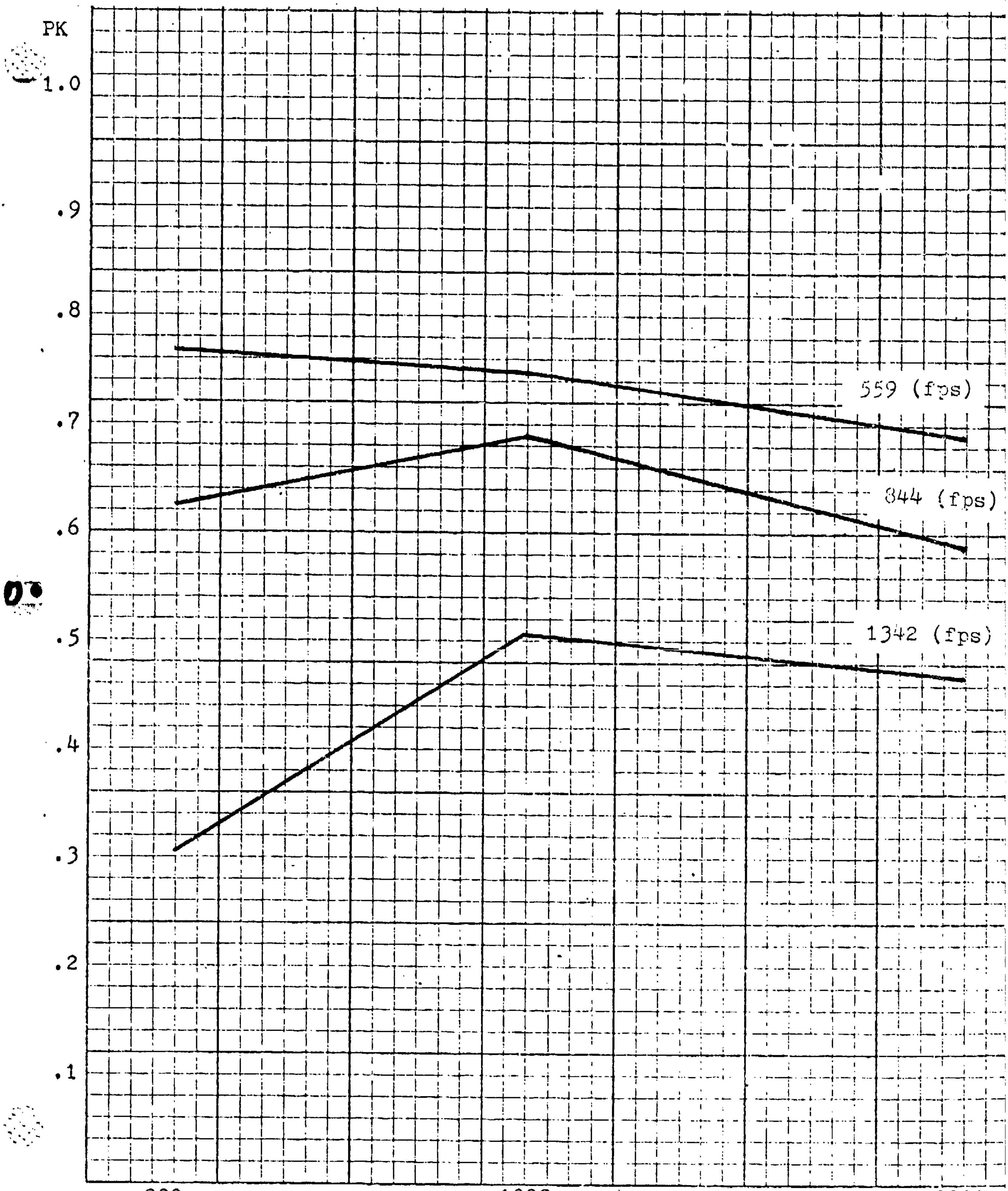


Figure 5-3 Test Case - Counter-Intuitive PK Curve

means that the distance from ADU to aircraft is greater, and as range increases, the PK decreases. The tradeoff is situationally dependent. The distant range may be the major determinant for one site, while the increased number of shots may be more important at another site. The situationally dependent tradeoff is influenced heavily by the firing doctrine and behavior of the ADU. This is a major consideration. The smartness of the ADU (how it fires) will determine which side of the tradeoff is dominant in calculating PK. The issue of ADU smartness needs to be explored further.

This reasoning suggests that the ADU needs to delay its fire (to be smarter than it has been) and wait until the aircraft has penetrated farther into the engagement envelope. This could be accomplished by increasing the initial reaction time for a site (forcing it to wait), by decreasing the maximum effective range of the site, or by slowing down the site's rate of fire. If the reaction time for the site were increased, that would discriminate against aircraft that were flying directly towards the ADU. These aircraft would be in the engagement envelope for a longer period of time. The ADU would wait a relatively long period of time, then shoot and continue shooting. The aircraft that spent a longer period of time in the engagement envelope would receive more than a proportionate share of the fire. Aircraft flying

tangential to the ADU (intercepting the engagement envelope at a relatively large offset distance from the ADU) would perhaps not even be in the envelope long enough to have a shot taken at them. This approach is wrong. Even if the aircraft was only in the engagement envelope for a short period of time, the site should fire at least once. This approach eliminates all the shots (even if there would have been only a few) taken at those aircraft that are flying past the ADU at an offset. The very distant shots taken at aircraft that are in the engagement envelope for longer periods of time are eliminated. Eliminating all of the shots at the offset aircraft, just to reduce the number of ineffective shots taken at aircraft that stay in the envelope longer, is unrealistic.

The same problems would exist if the maximum effective range of the site were decreased. Aircraft that originally traveled through the engagement envelope offset from the ADU might not be in the engagement envelope at all after the change of effective range. While the aircraft flying directly into the engagement envelope would have a more realistic series of shots taken at them, the aircraft skirting the envelope would not. There are enough cases of both types that both cases must be considered. No tradeoffs exist. At the very least, changing a data value that reflects some aspect of the real system defeats the purpose of a study.

By slowing down the ADU's rate of fire, initial shots at long range would still occur, but succeeding shots would be spread out over time. For the aircraft flying into the engagement envelope, the initial shot would represent an exploratory shot testing the range capability of the ADU. Succeeding shots would be taken as the aircraft continued to penetrate, and the shots would increase in effectiveness. The increased time between shots insures that all of the site's munitions are not expended at great distance; rather that the site waits until it has better, more potentially lethal, shots. For the aircraft penetrating at an offset, the site will still fire at least once. This (single) shot is the only shot that will be fired with either of the specified values for time between shots. The offset dictates that the aircraft will be in the engagement region for a shorter time than if it flew directly at the site. When flying at an offset, only a few shots can be taken; so there is not much concern about taking a large number of ineffective shots. For these reasons, increasing the time between shots is the preferred method of delaying and spreading out the ADU fire.

After increasing the time between shots, the same set of test runs used for the previous tests was resubmitted. There were changes in the PK trends and relationships, but they were only minor and no new or more useful conclusions

could be drawn. It was observed that, of the AAA guns that fired, the great majority always fired their munitions limit. This observation implied that, if the site had more available munitions, it would continue to fire. The shots that would have been taken had the site not run out of munitions might or might not have been more effective than the shots that were taken within the munitions limit. Therefore, a series of tests were run where munitions were not limited. The ADUs fired on the aircraft as long as the aircraft was in the engagement envelope. When this happened, the number of shots increased tremendously, as did the PK. Some subset of shots per site had to be extracted to provide a realistic PK. The choice of subset represents the firing doctrine and smartness of the ADU. The subsets that were used were blocks of twelve shots. Twelve is the arbitrarily defined munitions limit on AAA sites. The AAA site limit was used because it was the AAA types that were firing to their limits. The blocks used for PK calculation were taken at the earliest and latest firing opportunities.

The earliest firing opportunity block was chosen in order to examine the PK values associated with a "dumb" ADU. The latest firing opportunity block was assumed (correctly) to be a closer block of shots than the block for the earliest opportunity and, as such, permits an examination of a smarter ADU. Note that, in general, this

second block is not guaranteed to be the best block of shots to evaluate. The best block is bracketed by these two options.

The twelve shots that should be evaluated to obtain the PK due to a site employing an intelligent firing doctrine are those that occurred at the shortest range. The shortest range shots occur on either side of the point where the aircraft begins to recede from the ADU. Up until that point, the aircraft was approaching the ADU and the ranges were decreasing. When the aircraft begins to recede, the ranges will begin to increase. The best twelve-shot block should straddle the point on the flight path where the aircraft begins receding. Six shots should be taken on either side. This is the logically apparent way to determine the shots that are to be evaluated. In this beddown, however, the ADUs were not positioned so that this approach is feasible.

The air defense units seemed to be placed in positions where there was good forward vision, poor lateral vision, and even worse backward vision. Figures 5-4, 5-5, and 5-6 display the LOS regions at 200 foot altitude for three of the most active AAA sites in the test beddown. The dark areas are the points in space where the aircraft would be unmasked to the given site. The ADU is the small circle within the darkened LOS region. Grid north is in the positive Y direction, and

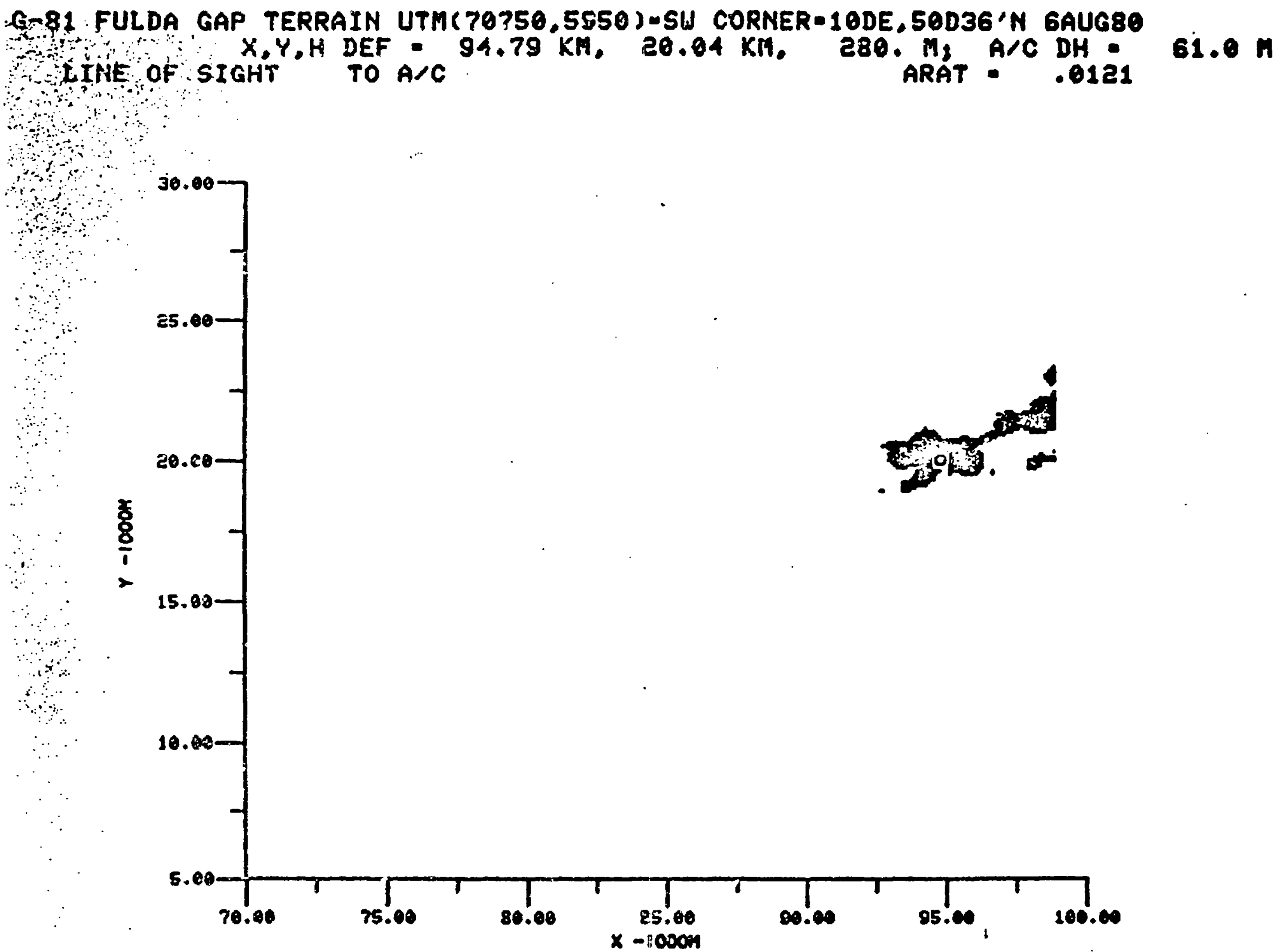


Figure 5-4 Sample LOS Region - ADU 4

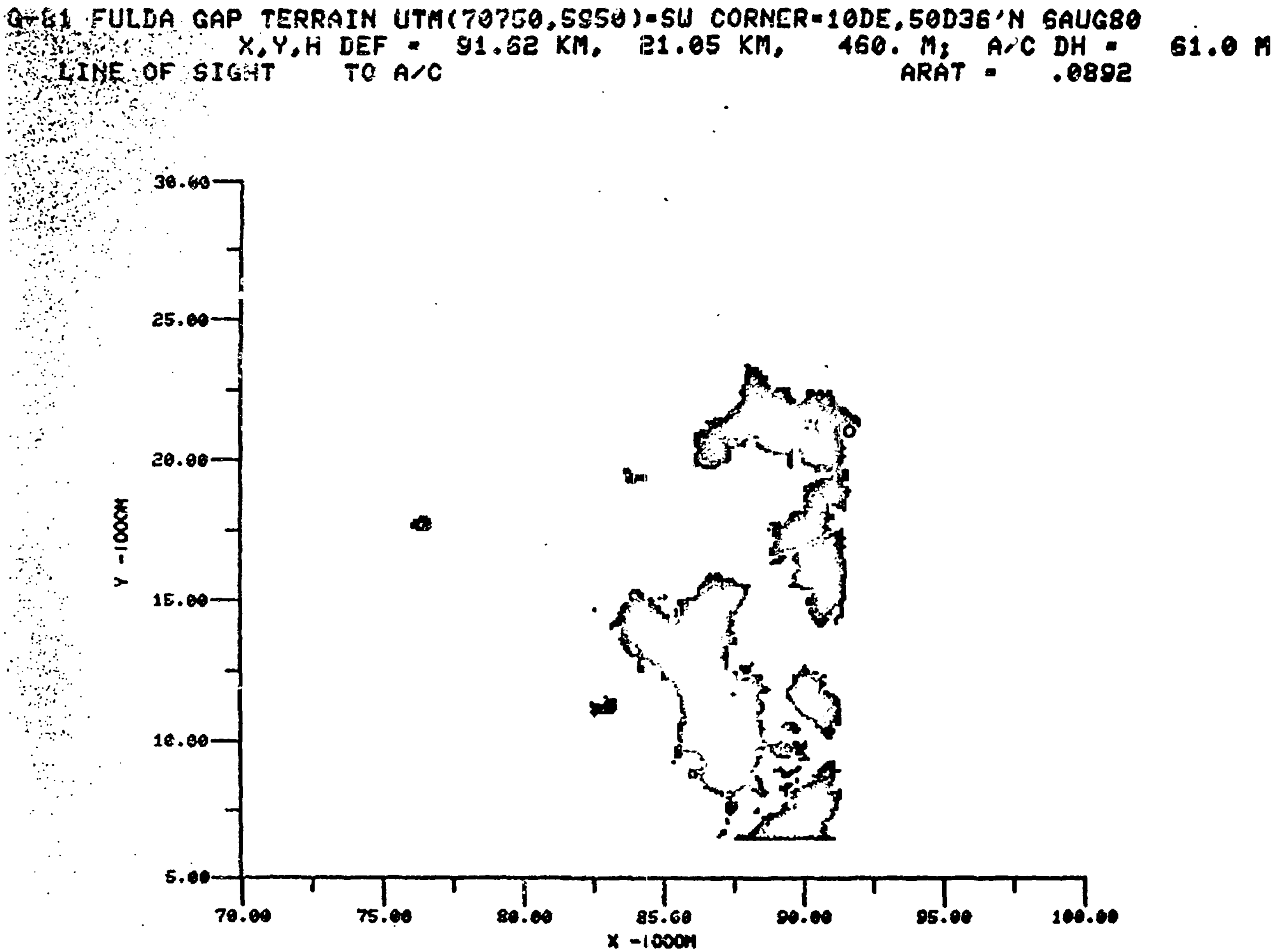


Figure 5-5 Sample LOS Region - ADU 11

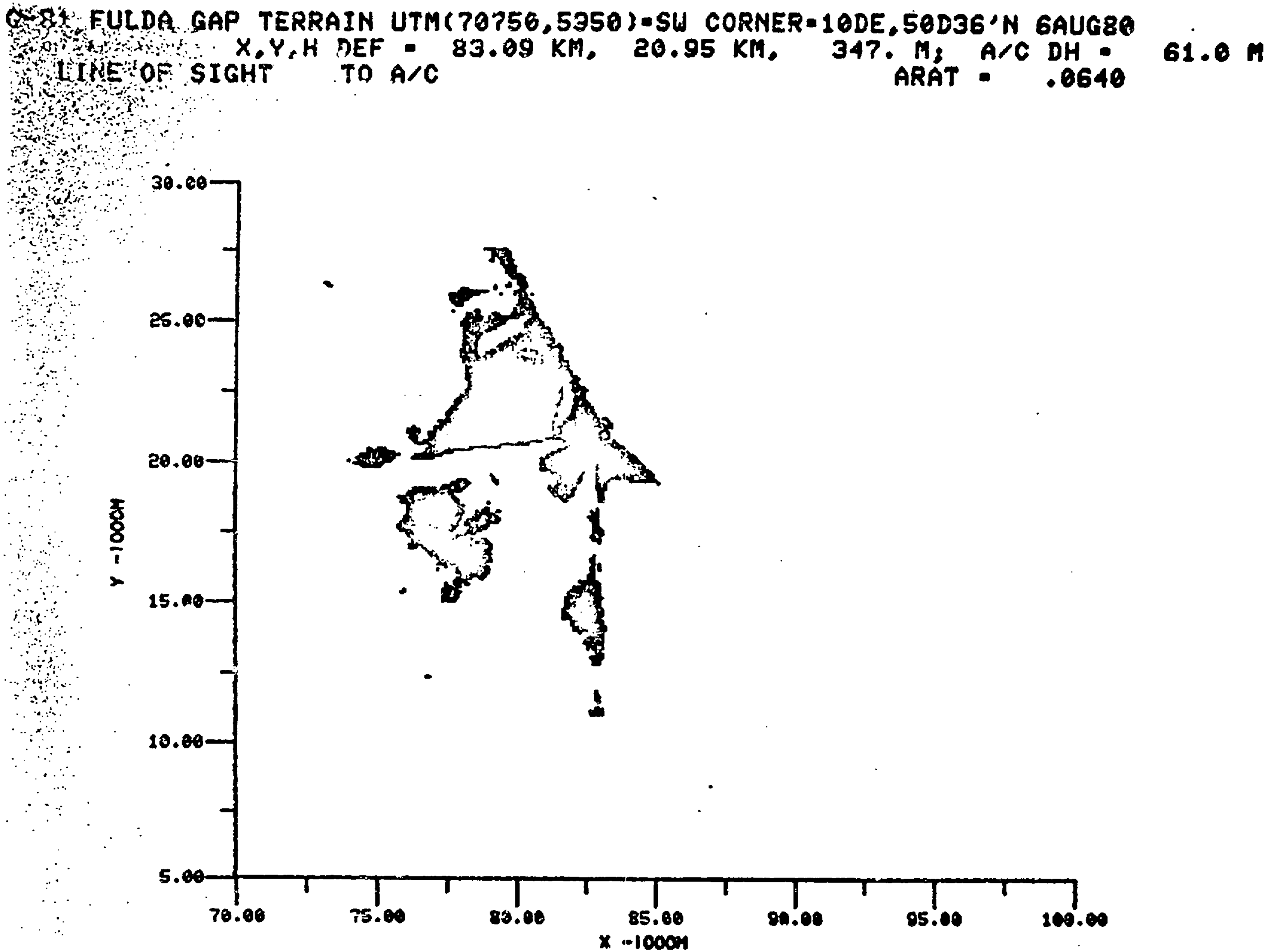


Figure 5-6 Sample LOS Region - ADU 17

the aircraft travels in the positive X direction. When the LOS region is limited, the engagement envelope is also limited. In this case, the engagement envelopes are generally restricted to the forward looking hemisphere of the site. As a result, faster flying aircraft exited the engagement envelope before a site could utilize all of its weaponry. Many sites could not take shots at targets after they passed more than 50 degrees off the ADU's primary look direction. This means that the last twelve-block contains the best twelve shots that could be taken. Using these blocks to evaluate PK gives the best upper bound on PK possible. This situation holds for almost every ADU in the beddown.

Establishment of a Base Case

Scenario. Using the twelve-shot blocks allows ADU smartness to be addressed. It also provides the means to complete the discussion on the counter-intuitive PK results and establish a base case against which sensitivity runs can be compared. The previous set of tests was augmented with a no-ECM case to provide a control case or another point of comparison. The radar footprint used is relatively large but starts close in to the aircraft. The ADUs are firing continuously in order to provide the data from which to extract the twelve-shot blocks. After the blocks have been extracted, the firing

doctrine is viewed as shoot-look-shoot with very short assess time. Reload, reaction, reacquisition, and break times are kept constant at nominal values. The beddown that is used represents a typical second echelon deployment of air defense units. The ratios of site types and their geographic positioning reflect what one might actually expect to see (within the limits of unclassified data). ASD/XR currently uses this and similar beddowns for analyses of this kind. Two flight paths were used for both the ECM and the no-ECM cases. Results for both flight path runs were similar, so only the more illustrative cases will be reported.

Case 1. Figure 5-7 presents the PK curves for the no-ECM case with the first twelve shots of all weapon types contributing to the PK. PK is listed on the ordinate and commanded clearance altitude (HO) in feet on the abscissa. HO ranges from 200 to 2000 feet. Ordinarily, HO values would be less than 500 feet, but a wide range of values was used to provide a control or contrast against the lower HO values. The contrasts provide a means to eliminate the PK anomalies at lower altitudes and an aid in interpretation as altitude increases. On each graph there are three curves corresponding to aircraft velocities in feet per second of 559, 844, and 1342 or Mach .5, .75, and 1.2.

One would expect to see PK curves that increased

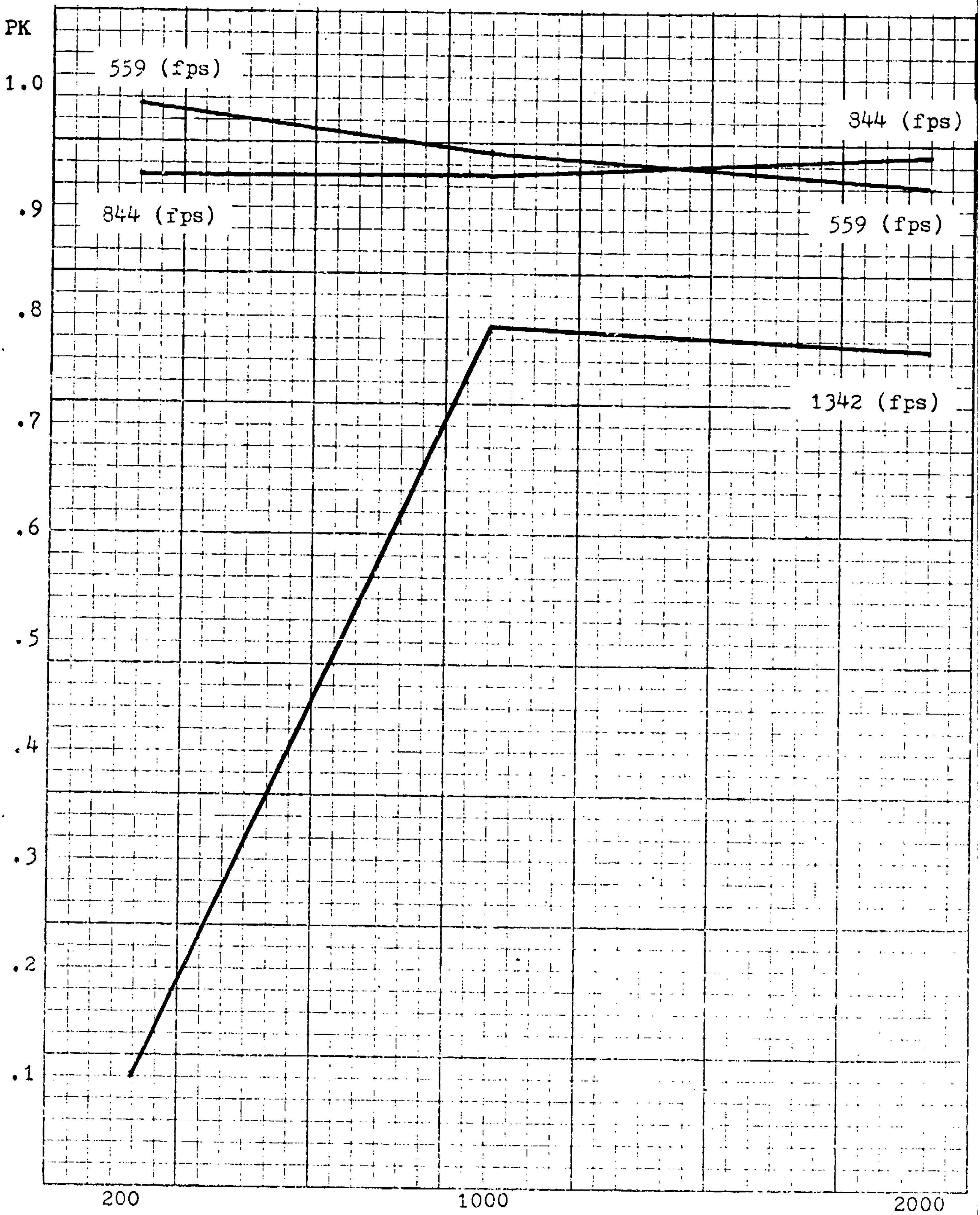


Figure 5- 7 First 12 Shots - No ECM - All Weapons

monotonically with altitude and decreased monotonically with velocity. In addition, the PK values should correlate with shot opportunities, and shot opportunities should correlate with exposure time. Exposure time was the measure of effectiveness used by MODIFIED TERRAIN in its vulnerability form. Exposure time reacts as expected to changes in velocity and altitude; therefore, exposure time is another good measure for comparing shot opportunities and PK values. Figure 5-8 displays the exposure time curves for Case 1.

The 559 curve in Figure 5-7 shows PK decreasing with altitude. PK increases with altitude for the 844 curve. PK increases and then dips slightly for the 1342 curve. At altitudes somewhere between 1000-2000 feet, the PK values for aircraft traveling at 559 become less than the PK values for aircraft traveling at 844. With this exception, the PK relationships between velocity curves are intuitively acceptable. The questions that are raised by these observations are: why does the 559 curve decrease with altitude, why do the 559 curve and the 844 curve cross, and why is the 1342 curve non-monotonic?

Partial explanations for these questions exist. This graph tracks the PK for the first block of shots taken by the ADU. As the aircraft's altitude increases, the ADU sees the aircraft sooner, and the first twelve shots occur at a farther range from the ADU. As the range increases,

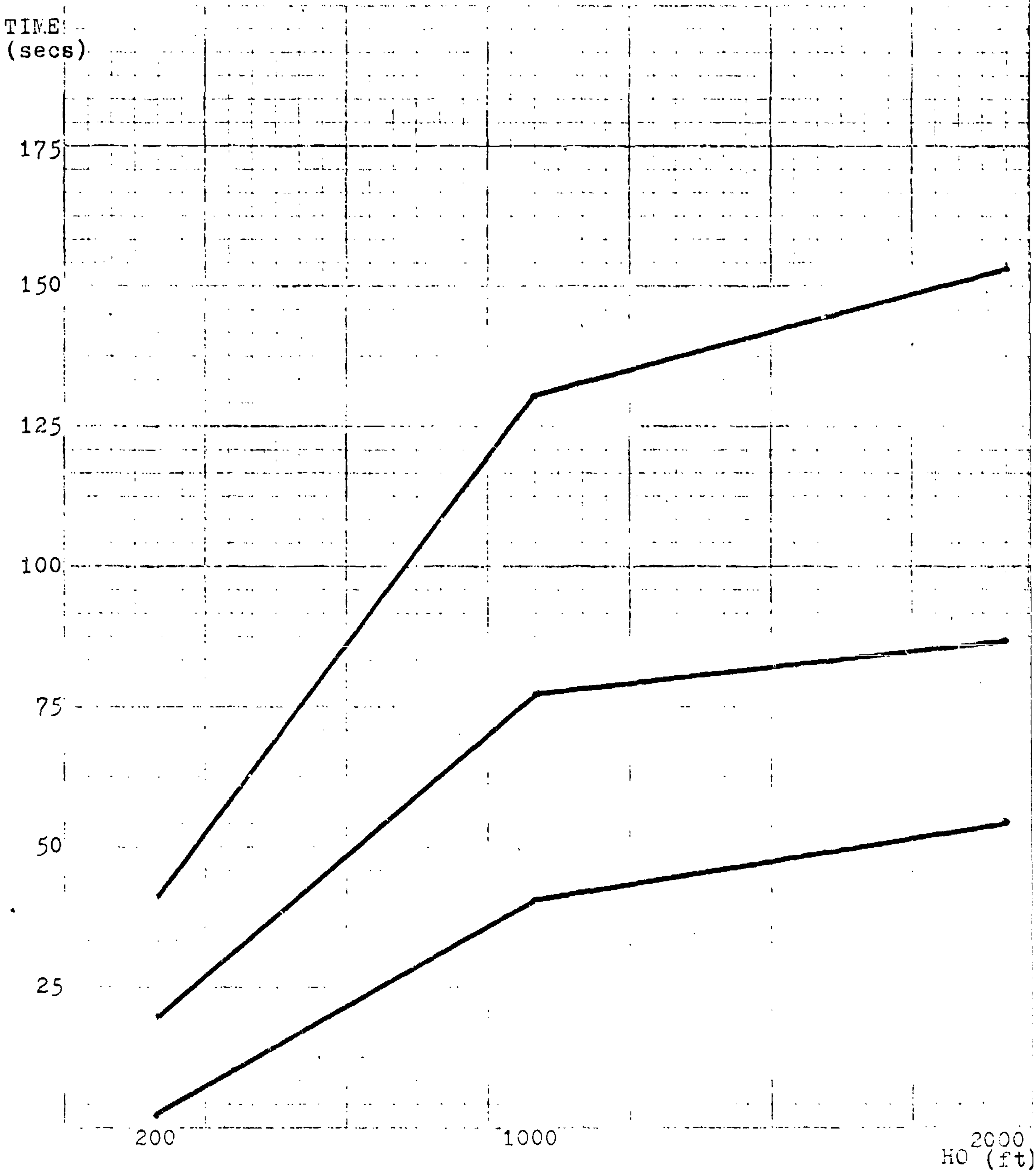


Figure 5-8 First 12 Shots - Exposure Time

the PKSS decreases, and thence the PK. This explains the 559 curve. Why then do the 844 and 1342 curves behave differently? The 559 curve slopes downward because the shots taken at the aircraft occur progressively farther out as altitude increases. For the 844 and 1342 cases, the initial fire point is farther away, but the aircraft is moving toward the sites faster and cuts the range on the shots down faster. For the 844 case, this results in shots in the latter part of the block being more lethal than the corresponding shots for the 559 case. Given this explanation, one would expect to see the 1342 curve being even higher than the 844 curve as altitude increases. This is not the case. The aircraft flying at 1342 approaches the ADU sites faster which improves the effectiveness of the shots that are taken; however, the number of shots that are taken decreases so that there are not as many close, more effective shots being taken as there are farther, less effective shots. In these cases, the number of shots is a more heavily weighted determinant of PK.

If the explanations proffered for the relationships of the PK curves for the first block of shots holds, one would expect to see some changes as the method of calculating PK changes from inclusion of the first block of shots to inclusion of the last block of shots taken by the ADU. Specifically, those PK values and relationships

that were most affected by the distance from the ADU, the 559 and 844 curves, should change.

Case 2. Figure 5-9 presents the PK curves for the no-ECM case when the PK components are taken from the last twelve shots taken by each ADU. Notice that the 559 curve is now monotonically increasing, and at all points the PK values are greater than those recorded by the 844 curve. At HO=200, the PK values did not change from the first block calculations. Examining the detailed output from the model runs shows that, at 200 feet clearance, the aircraft maintained mask enough that no site took more than twelve shots. No difference in PK at this altitude could occur. At altitudes of 1000 and 2000 feet, there are definite changes in the PK values. The component shots of the 559 and 844 curves all occurred closer and were more efficient.

The 1342 curve did not exhibit any changes. This is again caused (or not caused) by the fact that no ADU attempted to take more than its allotted number of shots. This is intuitively pleasing since, at Mach 1.2, one would expect the aircraft to get into and out of the engagement envelope quickly and sustain few shots, which is what has happened.

The numbers listed in Table 5-1 represent the number of shots taken by each ADU in each scenario. These numbers represent the total number of shots taken without

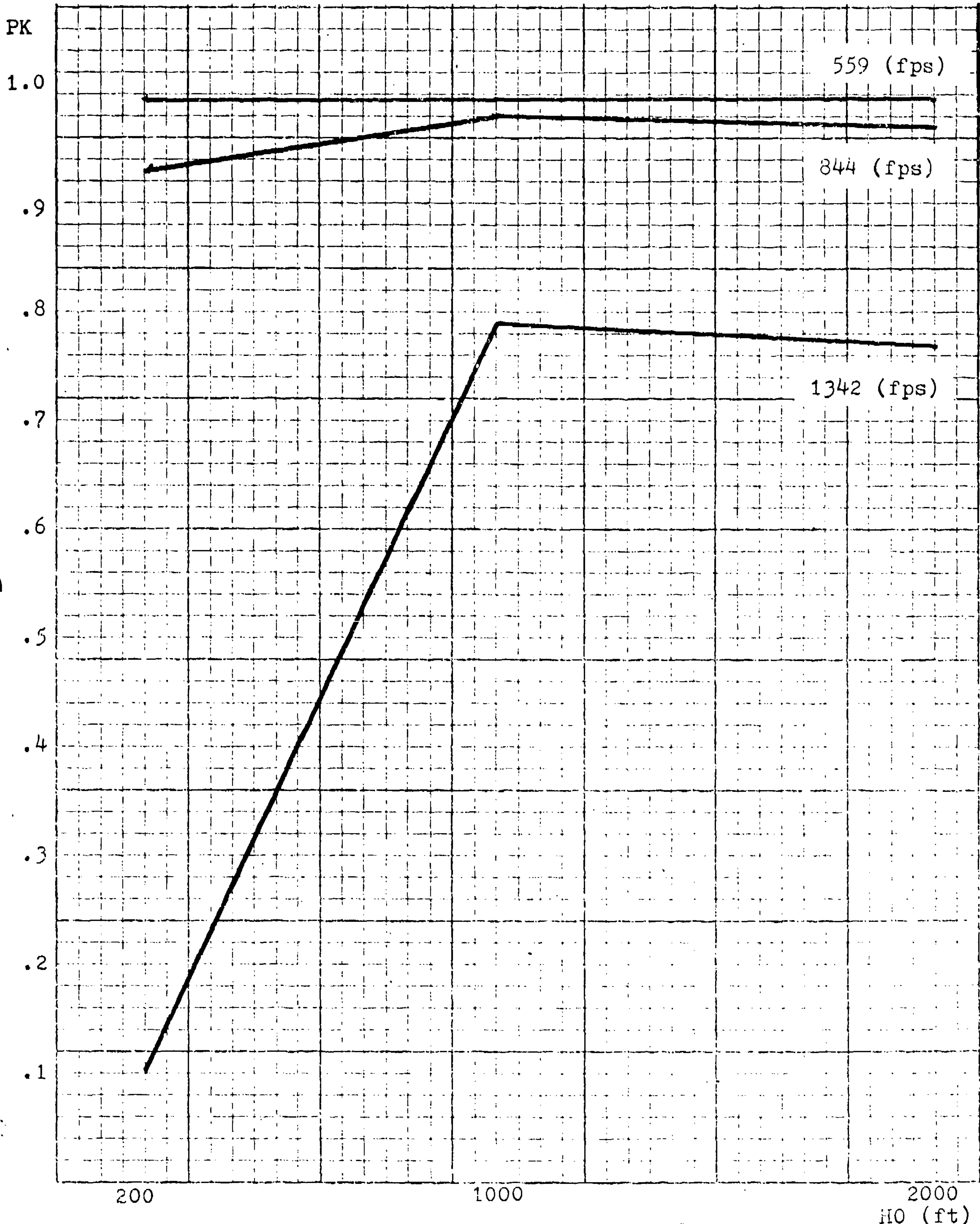


Figure 5-9 Last 12 Shots - No ECM - All Weapons

munitions limits. The PK values that are being discussed herein are taken as the first or last twelve of the series of values identified in Table 5-1. The total numbers of shots are also sub-totalled by ADÚ type: radar, IR, or AAA. ADUs 2-27 are AAA, 20-38 are IR missiles, and 39-40 are radar missiles.

TABLE 5-1 SHOTS TAKEN - NO ECM

	HO=200			HO=1000			HO=2000		
ADU#	V=559/844/1342			559/844/1342			559/844/1342		
2	9	5	2	20	15	10	20	15	11
3	0	0	0	9	4	1	17	11	6
4	5	2	0	22	16	12	22	16	12
11	6	2	0	22	14	6	22	16	12
17	9	5	0	21	16	12	21	16	12
20	0	0	0	0	0	0	1	0	0
21	1	1	0	1	1	0	1	1	0
22	0	1	0	1	1	0	1	1	0
37	1	1	0	1	1	0	1	1	0
38	0	0	0	0	0	0	1	0	0
39	2	0	0	4	3	1	4	3	1
40	0	0	0	0	0	0	1	1	0
RADAR	2	1	0	4	3	1	5	4	1
IR	2	3	0	3	3	0	3	3	0
AAA	29	14	3	57	53	41	61	58	53

Note that, in virtually every case, the number of shots taken by an individual ADU increases or remains the same as altitude increases. The number of shots taken by a site decreases as velocity increases. There are certain exceptions, such as the case at 200 foot clearance, where the number of IR missiles fired increases from 559 to 844. In the cases of these exceptions, the discrepancy is

always a difference of one. This difference is accounted for by the increase in the average and maximum clearance calculated by the terrain following algorithm due to the increased velocity. Note at the same time that, as the number of IR missile firings increases in those exceptional cases, the number of radar missile firings decreases. This is a function of ADU site deployment. The aircraft is not unmasked to the radar missile sites at the points in space where the terrain following algorithm generates terrain overshoot, whereas the aircraft is unmasked to an IR site at that point. The different sites see different volumes of airspace.

Examinaton of Table 5-1, particularly the missile sub-totals, indicates that the vast majority of shots being taken are by AAA sites. It seems necessary to examine the effect of guns only on the shape of the PK curves.

Case 3. Figure 5-10 depicts the guns-only PK curves for the no-ECM case. The guns-only graph is presented only for the last-twelve block of shots since it has been determined that use of the first-twelve block produces unrealistic, or at least undesirable, results.

After eliminating the PK components attributed to the missiles, the new curves are lower than the previous curves with guns. The only point on the graph where this generalization does not hold is the 200 foot value on the

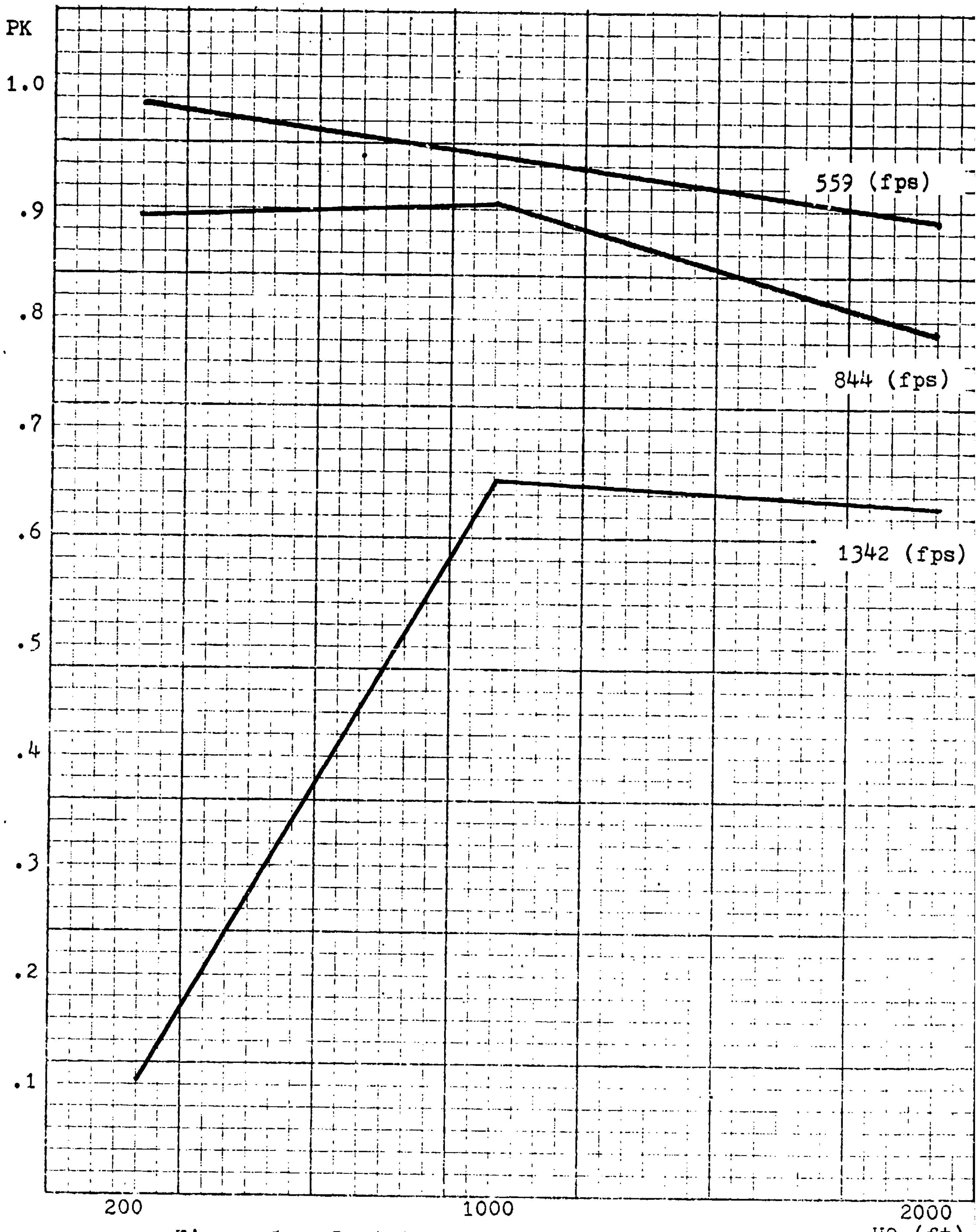


Figure 5-10 Last 12 Shots - No ECM - Guns Only

1342 curve. There were no missiles fired for this combination originally, therefore there are no missile PK components to eliminate. The other points at 200 feet are only moderately disturbed. There are only a few missile shots taken at the 200 foot altitude targets, and those are relatively ineffective especially when contrasted against the higher number of AAA shots being sustained. Eliminating the missile PK components for the higher altitudes of the 559 and 844 curves has a significant effect. The 559 curve declines in an almost-perfect, linear relationship. This is caused directly because of the distances from the ADU at which the shots occur. The higher the altitude of the aircraft, the further away the aircraft will be when mask is regained. The equation for PKSS for an AAA round is

$$PKSS = A/(A + 2\pi kR^2) \qquad (5\text{-}1)$$

where

A is the aircraft's average vulnerable area

k is the system error and ballistic error and

R is the ADU-to-aircraft range.

This equation is explained in depth in Chapter III (Equation 3-17). The equation has been rewritten here to emphasize the fact that PKSS is inversely proportional to range. As range increases, PKSS and PK decrease. The 559

curve exhibits this relationship.

The 844 curve is kinked. PK increases slightly from 200 to 1000 and then drops off again. As mentioned, the difference in PK at 200 feet between the all-weapons graph (Figure 5-9) and the guns-only graph (Figure 5-10) is relatively small, but still noteworthy. Breaking out the PK at 1000 feet shows a much larger loss in PK than at 200 feet, indicating that the missile PK values at this point were more significant. This is intuitively correct, since the aircraft is five times as high, is seen longer, and will draw more missile firings. The change in this curve due to the effectiveness of guns also makes sense. The aircraft is again flying higher and will take more AAA fire, therefore, the PK should be higher at 1000 than at 200 feet. The PK curve kinks at 1000 feet with values decreasing instead of increasing. The aircraft is now at an altitude where the distance from the ADU sites to the aircraft is a more important component of PK. In general, increased altitude increases PK by making the aircraft visible to the site sooner, and it decreases PK by increasing the actual ADU-to-aircraft distance. Both of these effects can occur at the same time and are situationally dependent. In this instance, the increase in ADU-to-aircraft distance when firing is a more sigificant determinant of PK than is the earlier exposure time.

It is useful to observe that the 1000 to 2000 foot portion of these two curves (and of the 1342 curve which will be discussed shortly) exhibits the same decreasing behavior. This behavior implies that, at all velocities, the altitude is a more significant determinant of PK through the PKSS equation than availability of shots.

When the missile contributions to PK are eliminated from the 1342 curve, PK values fall noticeably. There was only one missile shot to be eliminated from this case as opposed to six at the 844/1000 point, but the number of AAA shots was lower at the 1342 point; therefore, the single missile shot was a relatively major contributor to the PK value. The same explanation of behavior holds at 2000 feet; and, as noted above, the 1000 to 2000 portion of the curve is now decreasing.

It is now possible to see by studying the guns-only graph that it is the action of AAA which has produced the characteristic shape of the curves observed. There have been variations in PK due to differences from where in the stream of shots the components of PK have been extracted. The PK curves have shifted up or down as the effects of missiles were considered, but the shape did not change. That is, if the PK curve was kinked when missiles were included in PK calculations, it remained kinked when missiles were not considered. The only change was for the curve to shift up or down. The underlying form of the

curves has remained about the same. There is a basic understanding of PK curve variance and the influencing factors. The effect of ECM on the PK curves remains unexplored.

Having now examined the no-ECM cases and having established an understanding of some of the interactions and relationships of the PK determinants, one might change their expectations of the with-ECM cases. For example, straightforward monotonic relationships will not necessarily hold. What one would expect to see is that the number of radar missiles fired decreases. Additionally, the effectiveness of those that are fired should decrease.

Table 5-2 presents the number of shots taken by sites when the aircraft flies the previously used flight path and uses ECM. ADUs 2-17 are AAA, 20-38 are IR missiles, and 39-40 are radar missiles. The second set of totals for missiles and AAA provides the corresponding totals from Table 5-1 (for comparison).

The entries are virtually the same as Table 5-1, except the count of radar missiles has decreased or stayed the same. This bears out the first expectation mentioned above: use of ECM does reduce the number of radar missiles a site can fire.

TABLE 5-2 SHOTS TAKEN - ECM

	HO=200			HO=1000			HO=2000		
ADU#	V=559/844/1342			559/844/1342			559/844/1342		
2	9	5	2	20	15	10	20	15	11
3	0	0	0	9	4	1	17	11	6
4	5	2	0	22	16	12	22	16	12
11	6	2	0	22	14	6	22	16	12
17	9	5	0	21	16	12	21	16	12
20	0	0	0	0	0	0	1	0	0
21	1	1	0	1	1	0	1	1	0
22	0	1	0	1	1	0	1	1	0
37	1	1	0	1	1	0	1	1	0
38	0	0	0	0	0	0	1	0	0
39	1	0	0	2	1	0	2	1	0
40	0	0	0	0	0	0	1	0	0
RADAR	2	1	0	3	2	0	5	2	0
IR	2	3	0	3	3	0	3	3	0
AAA	29	14	3	57	53	41	61	58	53
RADAR	2	1	0	4	3	1	5	4	1
IR	2	3	0	3	3	0	3	3	0
AAA	29	14	3	57	53	41	61	58	53

Case 4. Figure 5-11 shows the PK curves for the with-ECM flight over the same flight path as used in the no-ECM cases. PK values are calculated with the last twelve shots taken by each ADU. Note that Figure 5-11 is virtually identical to Figure 5-10 (the no-ECM, guns-only graph). This result conforms to expectations. The guns-only graph eliminated the effects of missiles by recomputing the PK values without the missile components. Running the MODIFIED TERRAIN model with ECM does the same thing. The accuracy of radar missiles is degraded, and so, therefore, are the PKSS values. The overall PK in the

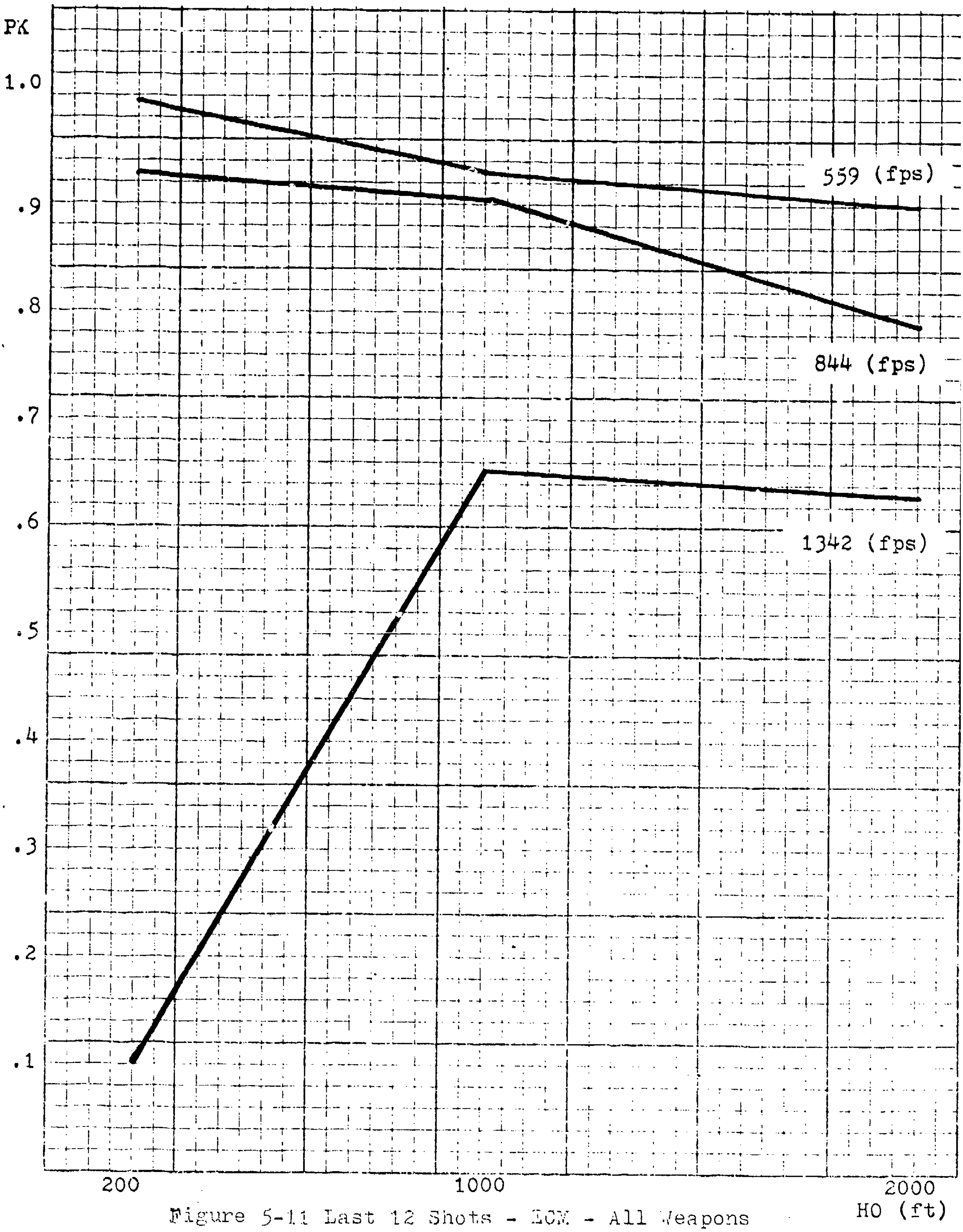


Figure 5-11 Last 12 Shots - ECM - All Weapons

ECM case is not significantly affected by radar missiles. The only exception to this generalization occurs at 200 feet on the 844 curve. The missiles fired in this case are not as effective as in the no-ECM case (see Figure 5-9 for graphical comparison). The no-ECM PK was .936, the with-ECM PK was .928. The difference is small, but the only possible cause of this difference is the change in ECM usage (remember, MODIFIED TERRAIN is a deterministic model). The magnitude of the difference is unimportant since PK values are relative to each other, and changes and trends are the important results.

At the same time that the ECM PK is less than the no-ECM all-weapons case, it is also greater than the no-ECM guns-only case. Figure 5-12 compares the PK curves for the three cases at 844 fps. This fact indicates that, though there were radar missiles fired and their effectiveness was degraded from the no-ECM case, the degree of degradation was not such that the missiles were totally ineffective. The missiles did contribute something to the overall PK; thus, the PK value was greater than the previous guns-only value. The other observation made in the no-ECM guns-only case still holds. When missile effectiveness is degraded, the PK curves shift down and flatten out. That is, as the number of components of PK are reduced, so is the PK.

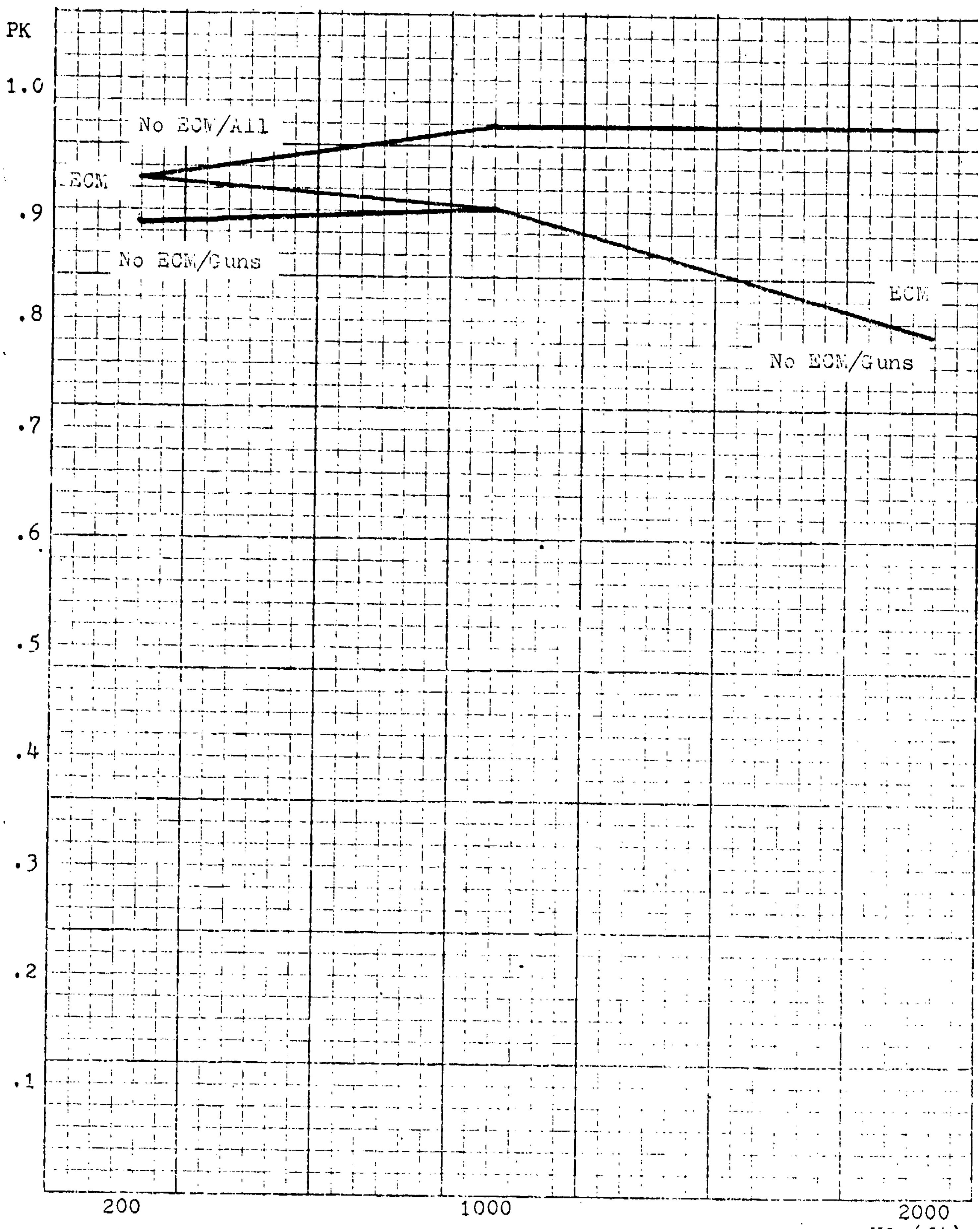


Figure 5-12 Overlay of 844 PK Curves: Figs 9, 10, 11

VI Sensitivity Runs

Now that most of the basic interactions of altitude, velocity, ECM, and terrain following are understood, some examination of the sensitivity of this base case to changes in other parameters can be studied. The parameters of interest are those that were highlighted in Chapter IV; namely the radar footprint, changes in IR signature and required lock-on range, RCS reduction, the size of the AAA salvo, the ADU site reaction time, the required loss of LOS time to break lock, the munition limits, the firing doctrine, and the shoot-look-shoot assessment time. Appendix E details the design of the sensitivity test runs, and Appendix F tabulates the PK results of each of those runs. This section will summarize the important results from Appendix F.

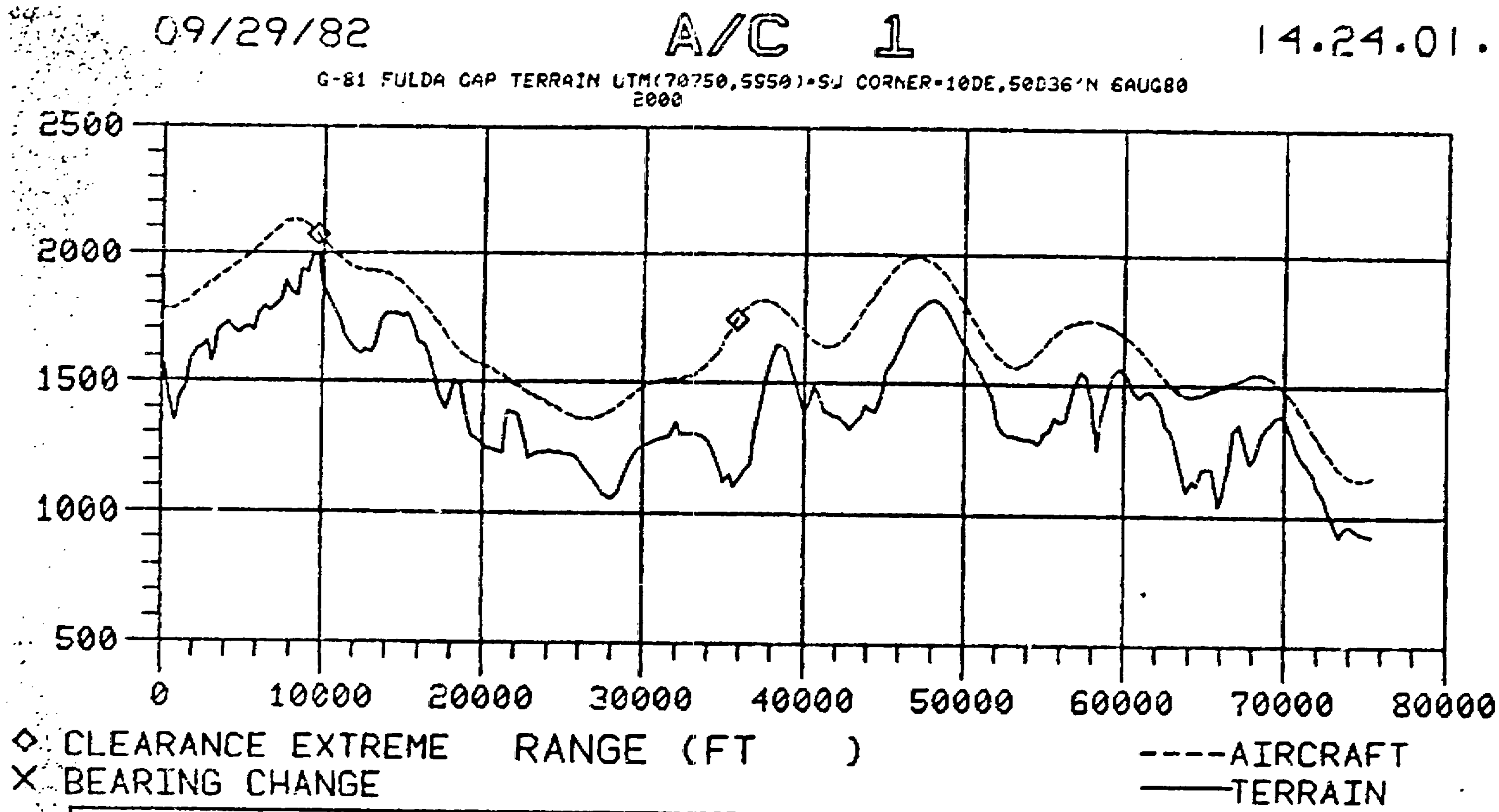
Footprint Tests

Runs 1, 2, and 3 investigated the effects of changes to footprint size and location and were actually accomplished before the series of base case runs. This was required in order to determine a common footprint that would be usable with all altitude and velocity combinations. As was explained in Chapter IV, the correct minimum look distance had to be determined so that the radar would not look beyond immediately approaching

obstacles and as a result fly into them. A feasible incremental look distance was also required so that the radar would not be vision limited; so that it could look far enough ahead and prepare to make attitude corrections.

Run 1 (small footprint-short minimum radar range) produced a set of PK values in which there were no anomalies or unexplainable relationships. Run 2 moved the radar footprint out further and increased its size. This caused a problem at lower altitudes and slow speeds. Figure 6-1 displays the terrain under a certain flight path and the altitude profile of the flight path over the terrain at a clearance altitude of 200 feet and velocity of .75 Mach. Notice how the aircraft begins diving towards peaks in the terrain before it has passed over them and climbing away from valleys before flying over them.

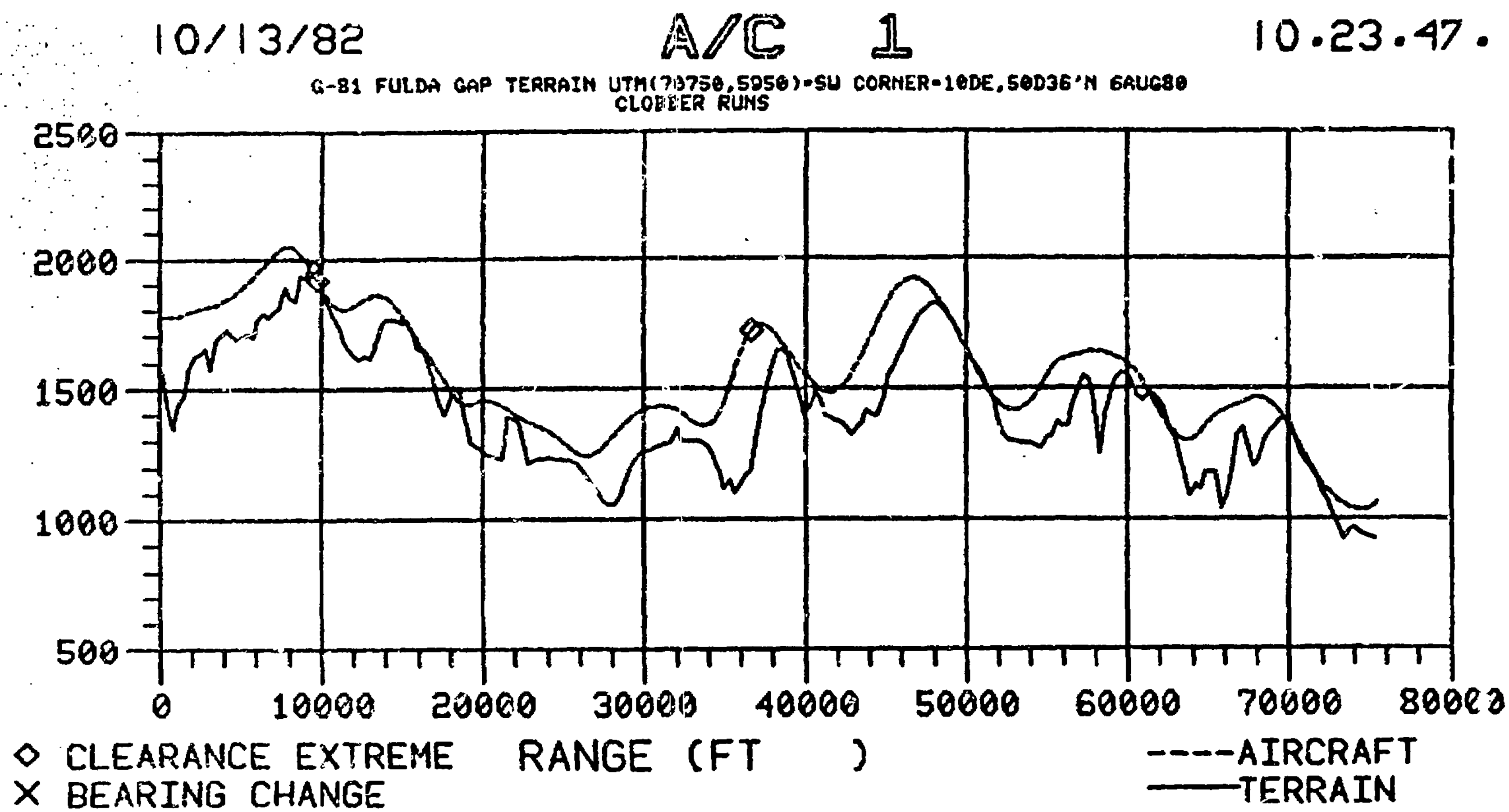
Figure 6-2 displays the same flight path and clearance but at .5 Mach. Note how the aircraft actually clobbers (flies irto the ground) on this flight path. The minimum clearance is 71 feet underground. No consistent or useful PK values can be extracted from such flight paths. The radar footprint in this case was placed too far in front of the aircraft for the velocity at which the aircraft was traveling. Figure 6-3 shows the distribution of clearance altitudes. The commanded clearance altitude was 200 feet, but the average clearance was 139. The



C1	= 1.300	VAC	= 844.0	SIGR	= .3060E-05	ADBPNM	= .2000E-04	D	= .3281
C2	= 1.740	STAT	=0.	F	= 4.000	RD3PNM	= .6000	TN	= .5000
C3	= 1.100	RNCL	= 5000.	BW	= .1396	STEPS	= 1.000	PRF	= .4900E+05
C4	=-.7700	TI	= .2500	RLOS	= 10.00	PRINTMTX	= 1.000	ACMIN	=-.8006
HO	= 200.0	XKGM	= .5000E-02	GDPT	= 2.000	RLM	=0.	ACMAX	= 1.500
RINC	= .1500E+05	TS	= .2500	XLAM	= .5743E-01	PAU	= 15.00	BD	= .2500E-03
RMIN	= 3000.	PT	= .3002E+05	CKT	= .4000E-20	TAU	= .3400E-06	ALPHAR	= .3048E-02
TP	= 2.250	PW	= .2000E-06	BWIF	= .2000E+07	ALPHA	= .4572E-03	RHCR	=0.
GMCL	= .3490	G	= 354.8	RIDE	= 1.000	TSYS	= .1000	GMDL	=-.5236
BMAX	= 1.500	SIGG	= .1000	BIAS	= .2000E-02	RHO	= .1000	DATS0	=0.

RIDE:HARD, MEAN= 249.9, STDEV= 97.3, MIN/MAX CLEAR= 82.3/ 620.6

Figure 6-1 Sample Flight Path Profile - Good Footprint



C1	= 1.300	VAC	= 559.0	SIGR	= .3060E-05	ADBFNM	= .2000E-04	D	= .3281
C2	= 1.740	STAT	=0.	F	= 4.000	RDBFNM	= .6000	TN	= .5000
C3	= 1.100	RNCL	= 5000.	BW	= .1396	STEPS	= 1.000	PRF	= .4000E+05
C4	=-.7700	TI	= .2500	RLOS	= 10.00	PRINTMTX	= 1.000	ACMIN	=-.8000
HO	= 200.0	XKGM	= .5000E-02	GDPT	= 2.000	RLM	=0.	ACMAX	= 1.500
RINC	= .1500E+05	TS	= .2500	XLAM	= .5743E-01	PAU	= 15.00	BD	= .2500E-03
RMIN	= 3000.	PT	= .3000E+05	CKT	= .4000E-20	TAU	= .3400E-06	ALPHAR	= .3046E-02
TP	= 2.250	PW	= .2000E-06	BWIF	= .2000E+07	ALPHA	= .4572E-03	RHOR	=0.
GMCL	= .3490	G	= 354.8	RIDE	= 1.000	TSYS	= .1000	GMDL	=-.5236
BMAX	= 1.500	SIGG	= .1000	BIAS	= .2000E-02	RHO	= .1000	DAT50	=0.

RIDE:HARD, MEAN= 138.9, STDEV= 108.1, MIN/MAX CLEAR= -71.9/ 526.7

Figure 6-2 Sample Flight Path Profile - Poor Footprint

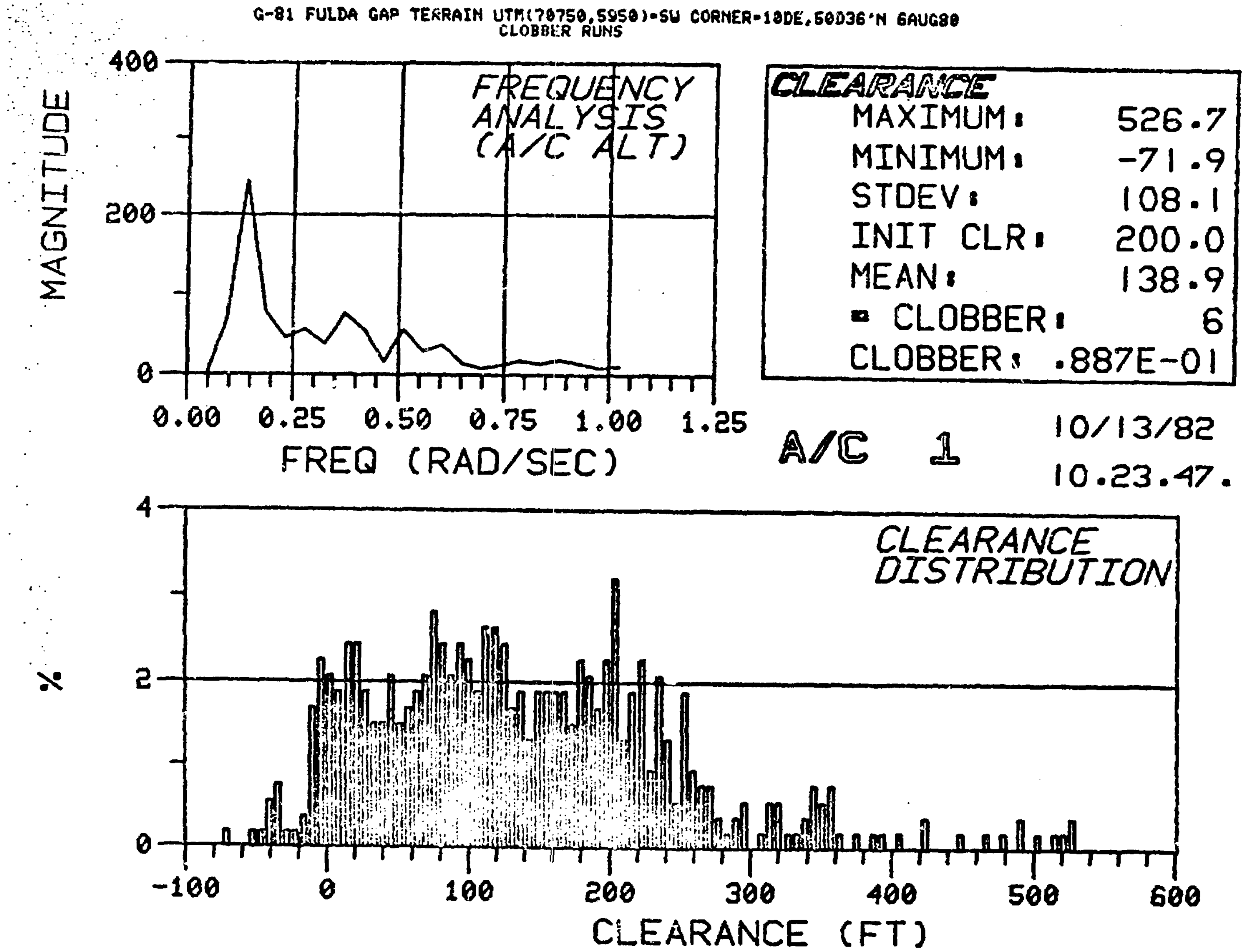


Figure 6-3 Flight Path Profile Analysis - Poor Footprint

clearance altitude histogram is shifted down on the altitude scale from the optimal. The clearances are much more densely distributed around, and below, zero. The probability of clobber is listed as .088, where a normal value is 10^{50}. The difference in magnitudes of the probabilities is an immediate danger signal.

The problems illustrated in Figures 6-1 through 6-3 are caused by the aircraft radar looking too far ahead for the velocity at which the aircraft is flying. The radar sees terrain changes, and the terrain following algorithm generates guidance commands to change the aircraft attitude to adapt to the terrain. The aircraft is not flying fast enough to arrive over the terrain features for which the terrain following algorithm is generating conformance commands. The fix to this problem is to fly the aircraft faster or adjust the footprint. One of the purposes of this model is to examine the effects on PK of velocity. Velocity must be varied. A fix in which velocity must be kept high contradicts the purpose of the model. The footprint is what should be adjusted, not the velocity. This implies that there is a good or best footprint for each combination of clearance altitude and velocity, and this is true. It is a difficult problem to determine the correct footprint for each altitude and velocity combination that will supply the same relative flight path profile changes. In a sensitivity analysis of

any kind, all parameters or influences must be held as nearly constant as possible so that interpretation of model output changes can be explained in terms of one parameter of interest and not include interactions with other parameters. This requirement of a constant footprint will not seem right to pilots, and rightfully so.

This (unrealistic) assumption of a constant footprint is required, however, so that model parameters can be varied and the changes in PK values examined ceteris paritus. When causes of changes in PK values have been isolated to one parameter, insights into the model operation are more apparent.

Run 3 brings the minimum look range back in, but leaves the incremental range out farther as it was in Run 2. The result of Run 3 are nearly identical to those of Run 1. The value of the minimum look range turns out to be critical and is specified at 1000 feet. The incremental range is not critical and, therefore, is specified arbitarily at 15000 feet.

RCS Tests

Runs 5, 6, 7, and 8 investigated the sensitivity of PK to changes in the radar cross section of the aircraft. RCS reduction can be viewed as a change in the effectiveness of ECM (Runs 5 and 7) or as an engineering

problem where the shape, size, construction, and composition of the aircraft are altered (Runs 6 and 8). Runs 5 and 7 leave ECM on and examine the effects of more powerful on-board ECM which reduces the RCS of the aircraft. RCS is reduced in Run 5 by a factor of 10 and in Run 7 by a factor of 100. Table 6-1 shows the reduction in number of shots, indicating the effectiveness of RCS reduction: no radar missiles are fired.

TABLE 6-1 MISSILES FIRED - RUNS 3, 5, AND 7

HO	Run 3 (Control) V=559/844/1342			Run 5 559/844/1342			Run 7 559/844/1342		
200	1	0	0	0	0	0	0	0	0
1000	2	1	0	0	0	0	0	0	0
2000	4	1	0	0	0	0	0	0	0

There were decreases in the number of missiles fired accompanied by small decreases in PK. The PK values at 200 feet and 559 fps for both Runs 5 and 7 dropped by 1%. All other PK values were unchanged. The small, isolated decreases are accounted for by the current effectiveness of ECM. The big reductions in RCS have basically no impact on PK.

Runs 6 and 8 examine the No-ECM case of PK sensitivity to changes in RCS. Run 4 provides the No-ECM control case. RCS is again reduced by factors of 10 and 100. Table 6-2 presents the number of radar missiles fired in these runs.

TABLE 6-2 MISSILES FIRED - RUNS 4, 6, AND 8

HO	Run 4 (Control) V=559/844/1342			Run 6 559/844/1342			Run 8 559/844/1342		
200	2	1	0	0	0	0	0	0	0
1000	4	3	1	0	0	0	0	0	0
2000	6	4	1	1	0	0	0	0	0

RCS reduction provides a big reduction in number of missiles fired. There is only one missile fired in Run 6 (compared to 22 in the control), and that single missile is eliminated by Run 8. As the missile firings are reduced, the PK values are also reduced (see Appendix F). The effectiveness of the RCS reduction is such that the PK results for Runs 6 and 8 look like the ECM control, Run 3, instead of the No-ECM control, Run 4. In the No-ECM case, use of RCS reduction techniques is extremely effective.

AAA Burst Size Tests

Runs 9 and 10 investigated the effects on PK of changes in the sizes of the AAA bursts. Burst sizes indirectly effect munitions drawdown; because as burst size and number increase, the munitions will run out faster. For these runs, the supply of munitions was assumed to be infinite. Instead, the number of bursts was limited. The assumptions required for these two runs are only subtly different dealing with the methods by which

munitions are counted. The effect on results and interpretation is nil.

As the burst size was changed, PK values changed almost linearly. When the burst size decreased from 20 to 12, the PK values went down considerably. When the burst size was decreased from 12 to 8, the PK values decreased proportionally. These results satisfy expectations, since it is known that the factor driving the PK results in this scenario is driven by number and effectiveness of AAA shots.

Reaction Time Tests

Runs 11 through 16 experimented with changes, by site type, in reaction time before initial firing. Runs 11 and 12 increased and decreased the reaction time of the radar sites. When the reaction time was increased, the PK values increased slightly at all velocities for altitudes of 1000 and 2000 feet. The most marked increases occurred at the lower velocities where the site held its fire longer and waited for the aircraft to get closer, so the shots were more effective. Conversely, the PK values decreased when the reaction time was decreased. This change allowed the sites to fire sooner at the more distant aircraft; therefore, PKSS and then PK decreased.

Runs 13 and 14 examined the IR sites. There were virtually no changes in PK. The big variable in IR

missile PK determination is whether or not a missile is fired, which depends on IR signature or lock-on range. Once a missile is fired, the PKSS is a predictable quantity. The CEP of IR missiles is not a strong function of the distance at which intercept occurs. Once again, an entirely new beddown and base case are needed to effectively discuss changes with IR missiles.

Runs 15 and 16 investigated the effects on PK of changes in the reaction times of AAA sites. As the reaction time went up and the target aircraft drew closer to the ADU, there were radical changes in the PK behavior. At 200 feet and 559, PK is virtually unchanged: the aircraft still presents itself to the AAA sites for long periods of time and is destroyed with high probability. As velocity increases, the PK values drop off drastically. The aircraft moves through the engagement envelope (which is already relatively small at 200 feet) quickly, and by the time the increased reaction time has passed, the sites cannot fire their normal complement. This is verified by the model output. Shot opportunities were decreased from 32, 14, and 3 to 24, 9, and 0 at 200 foot clearance.

At 1000 feet, there was no change in PK at 559, but a large increase at 844. The aircraft is higher and is seen sooner, but the reaction time delay throws the sequence of shots off just enough to allow the defense to take an extra shot (54 instead of 53). The number of shots

increases because the first shot that is taken occurs closer in than with the nominal reaction time. The closer firing range means that the time of flight is shorter, and the next shot can occur sooner. This process cascades all the way through the sequence of shots until just before the aircraft regains mask. At this point there is just enough time for one more shot to be fired. Hence, the extra shot.

The addition of that extra shot, combined with the increased effectiveness of the other eleven shots in the block, increases the PK at 1000 and 844 from .68 to .85. At 1342, the effect of the increased reaction time is to reduce the PK. The aircraft is flying fast enough to enter and exit the engagement envelope without sustaining as many shots as in the base case (36 vs. 41). At 2000 feet, the PK values decrease slightly for each velocity, reflecting the relative insensitivity of PK to reaction time changes at that altitude. The insensitivity is primarily due to the aircraft's altitude.

The occurrence of the PK jump at 1000 and 844 dramatizes the sensitivity of the model to timing delay of a particular sequence of shots by one or two seconds all the way down the line.

When the reaction times are decreased in Run 16, almost all of the PK values increase. The only exception is the case which presented the counterintuitive results

in Run 15 (altitude of 1000 and velocity at 844). Instead of increasing, the PK at this point decreased. This drop occurred for the same reasons, applied in reverse, as above. The model sensitivity to reaction time changes is again highlighted. Reaction time affects the points at which shots are taken. This is a crucial concept in understanding the PK trends.

Break Time Tests

Runs 17 through 21 investigated the effects on PK of changes in the time since LOS was lost that is required for break lock to occur. In these five runs, there were no variations in shot opportunities, exposure time, altitude extremes, or PK. The model output is totally insensitive to break lock time, at least in the range of values tested (see Appendix E) and for this scenario. The suspicion exists that, for other terrain or flight path selections, PK would indeed exhibit some sensitivity to this parameter.

Munitions Limit Tests

Runs 22 through 27 investigated the effect of changes of the limit on munitions on PK. Runs 22 through 25 change the limits on radar and IR missiles. In most cases, the number of missiles fired is nowhere near the site limitation; therefore, changes on the munitions limit

is ineffectual. When decreasing the limit does not cause a shot that might have been fired to be lost, the effect on PK with respect to the existing PK contribution from AAA is negligible. A change of flight path or a concurrent change of firing doctrine or rate could cause a change in PK.

Runs 26 and 27 change the munition limits on AAA sites. Since it has been shown that PK for this scenario is heavily dependent on AAA fire, it is to be expected that munitions limit changes will produce definite changes in PK. Such is the case. As the number (not size) of AAA bursts allowed increases, the PK values increase, except in the five cases where altitude is 200 or velocity is 1342. These five exceptions are the cases where no more than twelve shots were taken originally, so increasng the limit makes no difference in the number of shots taken or the PK. The other four PK values increase; and, except for the 1342 curve, all PK relationships satisfy the intuitive expectations (monotonicity). When the munitions limit is decreased in Run 27, PK values decrease except in the 200 foot cases where the limit was still not exceeded. The six values that did change did so in such a manner that the PK relationships for the 559 and 844 curves are still monotonically decreasing but are shifted down considerably. This conclusion makes sense: fewer munitions, fewer shots, therefore smaller PK.

Shoot-Look-Shoot Assess Time Tests

Missiles. Runs 28 through 31 investigated changes in PK based on changes in the shoot-look-shoot assess time for missiles. For the ranges of these values that were tested, there were no changes in PK, no sensitivity. The lack of sensitivity exists because there were very few cases where back to back launches of IR or radar missiles occurred. In the cases that did exist, the decrease or increase in PK was insignificant. In a scenario more heavily loaded with missiles or with a flight path that encountered a large number of missiles, this might indeed become a parameter which PK would be sensitive to.

AAA. Runs 32 and 33 changed the time between shots for AAA sites. Shoot-look-shoot assess time was not changed because AAA sites fire continuously, not with a shoot-look-shoot doctrine. When the time between shots was increased (Run 32), the number of shots taken decreased, as did PK. The exception was the slow velocity at the 1000 and 2000 foot clearance. Here, as before, there is a tradeoff between altitude causing increased exposure and an increased number of shots (and thence a higher PK) and the increased distance decreasing the effectiveness of a AAA burst. In this case, the distances are small enough that the increased exposure time is the deciding factor. For Run 33, the time between shots was

decreased. The number of shots went up for all altitude and velocity combinations and so did PK. PK is definitely sensitive to changes on the low side of the time between AAA burst but not on the high side.

Continuous Fire Mode Test

Run 34 changes the firing doctrine of the radar and IR sites from shoot-look-shoot to continuous fire and uses the old shoot-look-shoot assess times as the new times between fire. The only value affected by this change is for the 559 curve at 1000 and 2000 feet. The increase in PK at these points can be attributed to the high altitude and low velocity of the aircraft. At these extremes, the aircraft is unmasked to the site earlier and stays unmasked longer which gives the site an opportunity to fire more shots. The increase in number of shots results in an increase in PK. The increase in shots and PK is not evident at other altitude and velocity combinations because the aircraft is not visible long enough with respect to the specified time between shots. Run 34 now becomes the base case of comparison for Runs 35 through 38.

Firing Doctrine and Time Between Shots Tests

Runs 35 through 38 changed the firing doctrine of radar and IR sites from shoot-look-shoot to continuous

fire and examined the changes in PK values when the time between shots was varied. Run 35 increased the time between shots for radar sites. The PK values for the 1000 and 2000 foot entries of the 559 curve still increase but not as much as in Run 34. This is intuitively acceptable. Decreasing the time between shots for radar sites in Run 36 returns identical PK values as the base case. This indicates that PK is not sensitive to decreases in time between fire beyond 5 seconds.

Run 37 increased the time between shots for IR sites. The PK value at 2000 feet and 559 decreased from the PK value in Run 34. Again, it is only the high altitude and slow velocity combination that is affected. The PK fell because there was more time between shots and, therefore, fewer shots. In Run 38, the time between shots was decreased, and the number of shots and PK for the high and slow combination increased with respect to the PK of Run 34. In these two runs, the PK values are sensitive to increases and decreases in the time between shots.

Summary

This chapter has presented only a few of the possibilities of parameters that could be studied and only a few of the possible values of the parameters. As was seen, PK proved insensitive to many of the parameter values that were examined. Broader ranges of the

parameters need to be tested. In certain cases, entirely new beddowns need to be supplied. One important point to note is that all parameters were tested individually. There were no interaction effects allowed. This is effective for purposes of understanding the contributions of single parameters to PK, but does little as far as providing insight to the overall operation of the model.

VII Conclusions and Recommendations

Accomplishments

This study has provided five major products:

1. The models review and comparative chart (Appendices A and B) was the first major product to come out of this effort. In addition to the review of selected models, a set of generic characteristics and criteria were provided with which to compare any set of models.

2. Before making modifications to the original TERRAIN model, it was verified and validated. It was through this verification and validation process that the problem of inconsistently and incorrectly specified radar footprints was noticed. It was this realization that motivated Chapter IV. Chapter IV listed the factors that influenced PK, factors that might not have been fully understood earlier. These influences, when stated succinctly, increased the insights that one could draw on the behavior of PK. The data and calculations for analyzing vulnerability have proven to be correct. The results that are produced by different test runs are logical, consistent, and reflect reality or expectations.

3. The MODIFIED TERRAIN model was developed from the original TERRAIN model. The modifications

incorporated into the original TERRAIN model were radar detection of aircraft, missile launch logic, calculation of probability of kill as a measurement of survivability, and evaluation of the effects of ECM on detection of a target and the effectiveness (PKSS) of radar missiles.

4. A comprehensive user's guide for the MODIFIED TERRAIN model was produced (Appendix C). In the past there had been no existing documentation. This guide explains the operation of the model, what the user's options are, what the required inputs are, and what the outputs mean.

5. ASD/XR now has a framework (MODIFIED TERRAIN) with which to analyze terrain following penetrators in various air-ground battle scenarios. ASD/XR plans to continue development of the model as a tool for both vulnerability and survivability analyses.

Observations on the Modeling of the Air-Ground Battle

The MODIFIED TERRAIN model addresses the problems associated with fighter penetration into and through a ground based defensive array. Test runs for initial verification and validation were accomplished (Chapter V). Tests were run to examine the sensitivity of the aircraft's probability of kill to changes in the model parameters (Chapter VI). Now there are certain points

that need to be emphasized.

The determinants of PK were initially hypothesized to be the altitude and velocity of the aircraft. The effects of these two factors on PK, however, are not straightforward.

Altitude Effects. Altitude can affect PK positively. When the aircraft's altitude is relatively high, the ADU can see the aircraft sooner and for a longer period of time. When the aircraft is seen sooner, the ADU begins to take shots earlier and, therefore, may also take more total shots (up to the site's munitions limit). The total number of shots is further increased (again, only up to the site's munitions limit) because the aircraft is exposed for a longer length of time. PK increases proportionately.

Altitude can also affect PK adversely. In the case of AAA, PKSS is related inversely to range. That is, as range increases, PK decreases. When an aircraft flies at a relatively high altitude, it unmasks sooner and the ADU begins taking shots sooner. The shots that are taken are at a farther distance from the ADU and are, therefore, less effective than shots taken at a closer range.

Does the increased number of shots taken drive PK up, or does the decreased effectiveness of the distant shots keep PK low? This is the question that represents the altitude tradeoff with respect to PK contribution. This

question is answered by examining how velocity interacts with altitude to affect PK.

Velocity Effects. When the effects of velocity on PK are examined, the smartness of the defense must also be considered. When the aircraft unmasks at a relatively early point in time and the ADU begins firing, these initial shots are taken at relatively long range. If the aircraft were to increase velocity, the aircraft would get closer to the ADU faster, and PK would increase faster.

In the cases where the ADU begins firing at first opportunity and expends its complement of shots without restraint, the aircraft would do best to fly at slow velocities. The slow velocities would keep the aircraft at longer distances from the ADU while the ADU was busy taking relatively ineffective shots. By the time the aircraft reaches the ADU's optimal range, the site would have run out of munitions.

In the cases where the ADU practices some sort of smart fire control, the aircraft's wisest course of action is to increase velocity. Increasing velocity reduces the aircraft's exposure time. When the aircraft's first unmask is relatively close to the ADU, the aircraft can best reduce its PK by increasing velocity and getting out of the ADU's engagement envelope. In this case, increased velocity is the desired course of action, regardless of the ADU's firing doctrine.

ADU Smartness Effects. The important factors of ADU firing doctrine that interact with the altitude and velocity of the aircraft to affect PK are time between shots, reaction time, and most importantly, the number of shots taken and where in time they are taken. The ADU may use different combinations of these variables to enact different doctrines. These firing doctrines are usually prespecified. The ADU does not analyze each incoming penetrator and then adjust its method of fire to best advantage. The ADU uses intelligence estimates of how aircraft are expected to penetrate and sets its firing doctrine accordingly. In the same manner, penetrators have no firm information on how the air defense units will be firing. The aircraft's penetration is planned from its best available intelligence estimates of the ADU's doctrine. Neither the aircraft nor the ADU can gather information after the encounter has begun and change strategy. They must operate with whatever strategy was initially chosen. An accurate assessment of PK turns out to depend on what strategies are employed. Just how smart is the defense? How does t. defense plan its shots for high PK and no wasted or untaken shots? What size of an AAA burst is used, and will it vary as the distance to the aircraft varies? All of these are pertinent factors in the determination of aircraft PK, and especially so in this study.

Terrain Following Effects. The effectiveness of the aircraft's terrain following algorithm can affect the PK. When the terrain following flight path has a large number of substantial terrain overshoots the exposure time is increased. It follows that the number of shots taken and PK also increase. Overshoots are caused by inappropriate velocites or an incorrect specification of radar footprint in concert with an inappropriate velocity. These effects were discussed in Chapter V. The impact of overshoots on PK is not as important as the direct effects of altitude, velocity, and ADU smartness, but it is still an important factor.

Beddown and Flight Path Effects. The final major determinant of PK is the manner in which the threat is deployed and what flight path through the defended airspace is chosen. Beddown composition can be changed. Changes in composition will change the degree of influence of any particular weapon type. Beddown can also be changed with respect to ADU locations. Many air defense units in this scenario were backed up against terrain features which limited their LOS regions and affected PK evaluations. The flight paths that were chosen caused the aircraft to encounter certain air defense units and miss all the others. All of these factors introduce some (non-stochastic) randomness into the model. There are model parameters that interact and influence PK in a not

totally understood manner. These interactions are not easily held constant. A true control case may not exist. For instance, a flight path that happens to fly directly over an ADU will cause a higher PK than one in which the flight path is a kilometer farther away from the ADU. The PK in the second case may be virtually nothing and due only to a fortunate choice of flight path. A similar situation may occur depending on the type of terrain the ADU happens to be located in. If the terrain is very flat, the PK results should be fairly high (due to long exposure time from lack of masking) and easy to predict. If the terrain provides mask until the aircraft is almost over the ADU, then the PK may be drastically lower. The difference in PK will have been caused by the chance location of the ADU in that particular type of terrain. The point of this section is that there are chance occurrences in scenario formulation that can cause irregularities in expected PK results. Though these irregularities are relatively minor with respect to the influences of altitude, velocity, and ADU smartness, they do have an effect on PK.

Recommendations

I have several recommendations to offer. They will be presented categorically.

Model Operation. Some of the recommendations in this section are included for the benefit of any programmer that may continue development of the model.

1. Modify the calculation of RCS and IR lock-on range to take account of the three-dimensional aspect angle and increase the density of key data points used in (double) interpolations.

2. Include an internal switch in the model so that graphics may be toggled off or on. This makes it possible to bypass graphical displays and make large batch runs.

3. Put the ECM switch in the DAT common array DAT.

Modeling. The recommendations in this section provide suggested changes that may more realistically model the system. Included in these recommendations are changes to existing methods of calculations which are perceived to be less accurate than are required or are actually achievable.

4. Modify the PK calculation logic to use the best "n" shots as the PKSS contributors to PK, depending on the smartness attributed to the defense. This may be a difficult modification and may require

generation of a new model for each method of PK calculation.

5. Include an option to change the aircraft velocity, commanded clearance altitude, or any other parameter listed in Appendix D at the turnpoints of the input flight path. This option would be particularly useful if the user knew where the aircraft became unmasked to an ADU. The user could at that point increase velocity and exit the engagement envelope more quickly. This option would do away with the static-strategy constraint imposed on the aircraft.

6. The model does not currently check AAA sites to see if they have acquired a target, either visually or with radar. The only requirement for an AAA site to fire is that the aircraft be within maximum weapon range. Some change to model netted and autonomous fire control should be incorporated.

<u>Verification and Validation</u>. In my opinion, the MODIFIED TERRAIN model has not been completely verified or validated (due to time constraints). There are some relationships in the model that need further explanation.

7. Find the appropriate aircraft radar downlook angle, minimum radar range, and incremental radar range to use at the various altitude and velocity

combinations that preserve a consistent relationship between flight path profiles and reflect accurately the values that would be used in an actual flight.

8. Develop new terrain data bases for testing and verifying simple flight paths. For example, construct a perfectly flat scenario and analyze the PK trends in which there is no input by the terrain following algorithm; then construct a scenario where the aircraft approaches a site located on a plateau from an altitude below that of the site and then pops up over the site (Figure 7-1).

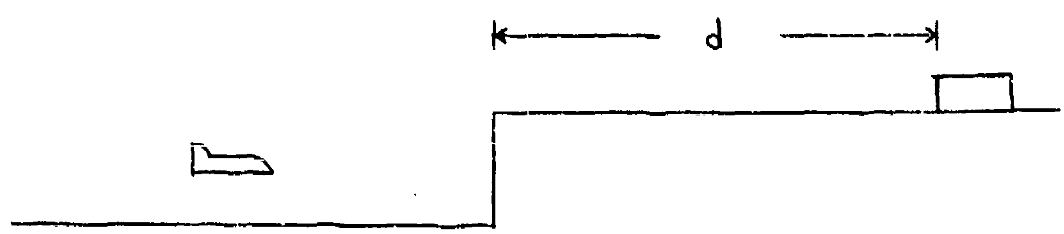


Fig 7-1 Proposed Terrain for Future Test

The distance d is the distance of the site from the vertical dropoff. The distance d should be varied through several values. The objective is to see the effects on PK of a controlled mask to unmask flight. The parameter d is used to control the distance at which the aircraft first becomes visible to the site. Alternatively, the aircraft can be flown in the

opposite direction to determine the effects on PK of a controlled unmask to mask flight. The results of these runs should provide information to help understand what happens when shooting at an aircraft that masks and unmasks, and to verify the behavior of the PK values observed in Chapter VI's sensitivity runs.

9. Develop alternate beddowns with different numbers of ADU types. One suggestion is to have a beddown with balanced numbers of each type of ADU. Another approach would be to construct three beddowns, one for each ADU type. Each of the three would be composed solely of one ADU type. Distribution of sites could then be addressed. This process would allow for more controlled examination of the effects due to a particular weapon type.

A second suggestion is to reduce the number of sites. This is a major new concept and reflects the fact that seldom will one single aircraft penetrate such a large defensive threat and be the only target. Usually there will be other targets in the air drawing fire, and no one will face the concentrated fire power of the entire defensive array.

CAUTION: There will be problems getting TERRAIN to accept alternate beddowns. There are some as yet unknown software-database requirements that must be

satisfied. I have been unsuccessful in getting either TERRAIN or MODIFIED TERRAIN to accept alternate beddowns.

10. Run similar beddowns, aircraft, terrain, etc. with MODIFIED TERRAIN, ZINGER AND P001 for validation purposes. Establish some benchmark values for PKSS and PK values.

Summary

As has been seen, the behavior of the TERRAIN model is influenced primarily by AAA guns, aircraft velocity, commanded clearance altitude, and ADU firing doctrine. The number of shots and exposure time correlate with the PK values. It has been shown that the aircraft PK is sensitive to flight path specification, and by extension, ADU location. Overall, the MODIFIED TERRAIN model seems to be effective, valid (as far as can be determined), and, as far as a tool for vulnerability analyses goes, reliable. Extending the model for use as a tool in extensive survivability analyses will require more complete verification and validation. The model could be used effectively to compare the survivability of: different airframes (F-15 vs. F-16), similar airframes equipped with different ECM systems, or similar airframes and differing beddowns. The defensive strategist can experiment with different ADU deployments to find the

widest coverage and optimum overlap. As the model stands now, it is adequate for small, high resolution studies of particular aspects of an ingressing aircraft's mission. When used as such, the analyst will have to study the model output closely to explain the behavior for each case. Requiring constant examination does require time and patience of the analyst, but it also keeps the analyst in touch with the fine points of the model operation and output and prevents the analyst from being blinded by the glory of the model and unquestioningly accepting its output.

The MODIFIED TERRAIN model performs well as a tool for analysis of aircraft survivability and vulnerability. As has been mentioned, further verification and validation would be valuable. Once this further verification and validation is completed, MODIFIED TERRAIN could be embellished to consider more sophisticated questions. Possible expansions would include attriting surface units, airborne air defense, more sophisticated ECM, and defense suppression. MODIFIED TERRAIN is constructed flexibly, so that it can be used for a variety of analyses. As with any major model, MODIFIED TERRAIN was developed to answer a specific question (aircraft vulnerability and survivability) and it does that well.

ASD/XR now posses a better tool for analysis of the aircraft survivability and vulnerability problem.

Although a great deal has been accomplished, there is more verification and validation work to be done. ASD/XR will be developing and using the model. Part of the additional verification and validation that I see as required will be accomplished there, but the amount of work that remains is great enough that others could become profitably involved.

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Appendix A

Literature and Models Survey

There is a large community within the Department of Defense concerned with SAM and AAA effectiveness and aircraft vulnerability and survivability. Headquarters Air Force, Tactical Air Warfare Center, Aeronautical Systems Division, Tactical Air Command, and many smaller military and civilian organizations have studied these problems and developed models and methodologies. These models range from the short, simple, analytic models to large, detailed, time-intensive simulations and families of simulations.

Types of Models

SAM models can be classified into three groups: fire analyzers, engagement simulators, and engineering models. Fire analyzers are models which estimate the spatial volume within which an aircraft is susceptible to fire by an ADU in terms of engagement parameters. Engagement parameters are variables such as aircraft velocity, aircraft altitude, intercept distance, missile launch angle, firing delay, etc. The aircraft trajectory is given as straight and level or a series of straight-line flight path segments. The missile trajectory given by proportional navigation approximates a collision course.

A proportional navigation couse is one in which the rate of change of missile heading is directly proportional to the rate of rotation of the line of sight from the missile to the target (Ref 11:475). A simple missile fly-out is used to obtain the missile time of flight. The missile time of flight in conjunction with the modeled firing doctrine determines how many launches may occur in a given site's launch envelope for an aircraft with the indicated profile.

Most fire analyzers are designed to provide analysis for specific threat systems, although there are those that can handle a variety of aircraft. Many aspects of the engagements in a fire analyzer are evaluated through table look-up procedures. The primary use of a fire analyzer is in the assessment of aircraft vulnerability and the number of launches achievable by a SAM system against that aircraft.

Engagement simulators are models which estimate engagement intercept miss distances and PK values. Simulators trace the interaction of target and missile over time and are influenced by flight parameters, design variables, and launch conditions. An advantage that an engagement simulator holds over a fire analyzer is that it does not require as many engineering estimates or standard value assumptions; the simulation generates its own values based on previous calculations in the simulation.

Engineering estimates are the best guesses available for the values of parameters that are currently unknown or associated with hardware that is not currently in operation. Standard values are descriptors of aspects of a system's operational environment or internal design parameters such as signal-to-clutter ratios in standard terrain situations, missile navigation constants, and missile fuzing parameters.

The basic distinctions between fire analyzers and engagement simulators are the manner in which aircraft flight, missile flyout, ECM, vulnerability, and survivability are assessed. The aircraft flight paths are usually constructed by another program and then input to the simulator. Missile fly-outs are more precise because of the use of higher order approximations in the guidance equations (equations of motion) or simply through the use of smaller time increments. Since most fire analyzers do not address ECM, the fact that the engagement simulator does introduces a higher level of resolution. The assessment provided in a simulator is usually accomplished by recalculating orientations, RCS, and jamming to signal (J/S) ratios at each time step. The primary advantage realized in the use of an engagement simulator is the more realistic inclusion and evaluation of ECM, survivability, and aircraft and missile motion.

Engineering models incorporate all available information on the operating characteristics of a system in order to achieve a more realistic assessment of the system. In models of this type, sections of the software are designed so that they can be replaced by the actual piece of hardware that is being abstracted. Engineering models typically include hundreds of transfer functions and play aircraft and missile motion with six degrees of freedom. Very few simplifying assumptions are incorporated in models of this type since the objective is to obtain very precise measures of the system effectiveness.

There are some drawbacks to using an engineering model. First, little simplification is used, therefore, the model becomes large, unwieldy, slow, and expensive to run. Second, development of a highly precise model may take nearly the lifetime of the operational system itself. Third, in order to insure the accuracy of output, the required inputs are often classified, and since classified computer facilities are scarce, analysis is limited.

The advantages in using an engineering model are that the outcomes of tactical situations can be known to a higher degree of confidence and the output of the simpler fire analyzers and engagement simulations may now be calibrated or validated.

Attributes and Areas Addressed

The three categories of models defined in the previous section encompass many different models and different modeling approaches to what is basically the same problem. Since the problem being studied by the classes of models is the same for each class, one would expect the characteristics of the methodologies used to study the problem to be nearly the same or at least to overlap to a high degree. The purpose of this section is to introduce and define a group of model characteristics which can be used to describe the organization and operation of any given methodology. Effort has been taken to include enough characteristics to provide adequate understanding of the operation of the model but not so many that the analyst gets caught up in information management and loses sight of his purpose. In 1977, Armament Systems, Inc. compiled a similar list of descriptors (Ref 3). The organization of descriptors used in their report is adopted for use here.

The order of the categories of descriptors is by function or purpose. The first category is the broadest and most aggregate, and the last is the narrowest and most specific. The sub-entries within each category are listed in order of increasing level of resolution. Table A-1 lists the categories to be presented.

TABLE A-1 CATEGORIES OF MODEL CHARACTERISTICS

1.	Purpose and use of the model.
2.	Program characteristics and how components of the air-ground battle are modeled.
3.	Aircraft characteristics.
4.	Ground weapon characteristics.
5.	Detection modeling.
6.	Results provided.

Category I discusses the purpose and use of the model. The sub-entries are:

1. Design modification tool: the program provides output useful for determining how the system being modeled should be changed in order to increase performance.

2. Force structure decision: the program provides output that can be weighed against established criteria. This may lead to modifications in existing force structure by size or type.

3. System/subsystem evaluation: the model is useful for comparing aircraft against aircraft or black box (parameters) against black box in terms of mission effectiveness.

4. System use and tactics: the program is useful in determining aircraft tactics (change in flight path, change in altitude, change in velocity, formation dispersal, etc.) and their effects on vulnerability and survivability.

5. Model language: this identifies the higher order language in which the model is written. FORTRAN includes

ANSI and machine dependent versions as well as different versions. Special purpose languages include SIMSCRIPT, SLAM, SIMULA, GPSS, etc. Other languages are captured in the original and descriptive class called Other.

6. Program size: this provides information on the number of octal words of core memory required to run the model. Small programs require less than 100K. Medium programs require between 100 and 200K. Large programs require 200K or more.

7. Portability: this describes whether or not the program can be taken off of one machine and easily implemented on another. The measure of portability is subjective and arbitrary but provides some rough idea of the effort required to change mainframes. A program is either not portable (excessive effort required for changeover, not worth the time), semi-portable (only minor alterations of machine dependent code), or totally portable (virtually no problems should be encountered). Portability takes into account differences in word size, language implementations, general availability of specific compilers, and machine size limitations.

Category II addresses the program characteristics and how the air-ground battle is modeled. The sub-entries are, in most instances, self-explanatory.

1. Air-to-surface attrition.

2. Surface-to-air attrition.

3. One-on-one.

4. One aircraft vs. many sites.

5. Many aircraft vs. many sites.

6. Two sided: the program plays air-to-surface and surface-to-air.

7. Terrain description: the program considers the underlying terrain for the specified scenario either in digitized or statistical format.

Category III discusses the characteristics of the aircraft; how they move and their state variables.

1. Maneuverability: the program considrs the degree to which the program accepts flight paths exhibiting changes in speed, altitude and direction. Changes can be interactive or generated off line. Often, the matter of degree is whether or not the program accepts flight path changes.

2. Vulnerable area: the program considers the amount of physical area which an aircraft presents that can be attacked and damaged. Vulnerable area is addressed either from an aggregate point of view, the entire aircraft, or is broken down into the vulnerable area presented by each component of the aircraft body.

3. Infrared signature: the program considers the intensity, frequency, and temperature of infrared emissions.

4. RCS signature: the amount of radar frequency (RF)

reflective surface area displayed by the aircraft as a function of aircraft orientation (aspect angle), distance, radar frequency, and relative velocity.

5. Optical signature: the program considers the physical profile of the aircraft, amount of light reflective surface, and glitter points.

6. ECM signature: the program considers the electromagnetic emissions of an aircraft, the frequencies, power, detectability, etc.

7. On-board countermeasures: the program considers whether or not the aircraft carries its own ECM or relies on escort or stand-off jamming.

8. Aircraft weaponry: the characteristics of the on-board weaponry (namely the types, trajectories, accuracies, and probabilities of kill) are played.

Category IV covers the characteristics of the ground weapons. The sub-entries are:

1. Weapon dispersion: the ground weapon installation may contain multiple, identical weapons in some pattern, or the ground weapons will be arrayed in separated sites with one or very few weapons per site.

2. Number of shots: the site is capable of taking only one shot at a time. The site requires some given length of time to recycle before the next launch. The alternative is for the simulation to provide for multiple shots/launches (salvos) considering interdependencies

between shots from gun tubes/TEL's (transporter erector launchers).

3. Firing doctrine: the program is governed by some set of rules associated with ground weapon firing schedules. The rules may include fire priority, number of rounds per burst, switch fire, etc.

4. Round limitations: the simulation recognizes that a limited number of rounds or missiles will exist at a site.

5. Reaction time: the program accounts for the time delay between acquisition and first fire.

6. Optical tracking.

7. Radar tracking.

8. Tracking limits: the program takes into account the limitations of the mechanisms used to track the aircraft.

9. Error considerations: the program requires specific accounting of component tracking and aiming errors as opposed to a single (or no) value that aggregates all component errors.

10. Linear prediction: aircraft and projectile paths are modeled linearly, possibly piecewise.

11. Projectile performance: the flight path of the projectile is explicitly modeled in terms of drag and gravity drop.

12. Intercept computation: the intercept geometry

solution is computed in the simulation as opposed to the alternative where aggregate intercept conditions were solved for in an off-line model, tabulated, and looked up in the on-line model.

13. Missile performance: the simulation of ground based missile velocity, acceleration, and g-loading is addressed.

14. Weapon location: the threat sites are specified with two- or three-dimensional coordinates.

15. Mask data: the simulation provides computations designating portions of the aircraft flight path which are masked to ground position by terrain and/or foliage.

.16. Rules of engagement(ROE): the program plays target priority considerations with respect to aircraft type and/or target selection (closest target, or target in range for longest period). The program utilizes option of firing at only priority targets or engaging non-priority targets if no priority targets are available. These considerations reflect the actual theatre ROE's at least at the point in time the model was developed.

Category V includes subcomponents of detection modeling.

1. Acoustic: aircraft detection and tracking is played based on the inputs of audio sensors.
2. Infrared.
3. Optical/visual.

4. Radar.

5. Meteorological effects: the simulation accounts for degradation of aircraft detection due to atmospheric conditions.

Category VI covers the results provided by the simulation.

1. Input data playback.

2. Flight path event history: the program provides a time log of masking status, altitude profiles for nap-of-the-earth or terrain following techniques, aircraft within effective range of defense, aircraft receives fire, aircraft returns fire, single shot PK values, comulative PK, and attrition point.

3. Ground weapon event history: the program provides a time log by defensive site when defections occurred, the site was masked (or conversely, an aircraft was not being tracked), aircraft within effective range, firing record, site received fire, and ground weapon PK.

Specific Models Reviewed

The previous section, along with the general classification definitions of SAM models, establishes a convenient framework for reviewing and comparing different SAM models. Model attributes and qualities can be assessed in a more standardized setting with this framework in hand. I will introduce, evaluate, and

compare a group of models culled from my literature review. A short summary will be provided for each of those models and will be structured loosely about the points outlined in this previous section. A chart structured according to the points of the previous section comparing the features of the models within this group will be provided in Appendix B.

The models that I present here are not the mo widely used, largest, most sophisticated, or standardized models in existence. They are very thorough in their purposes and are viable tools of analysis. They are, however, not well known in the modeling community due mainly to lack of exposure and advertising. These models are, in approximate order of increasing resolution:

1. SAM Fire Analyzer, produced for the Naval Air Development Center (Ref 1).

2. TERRAIN, developed by ASD/XR.

3. Generic SAM Model (GENSAM) produced for the Naval Air Development Center (Ref 1").

4. Air Defense Artillery and Defense Suppression Model (ADADS) developed within TAC (Ref 6).

5. Missile Intercept Capability Evaluation (MICE II) developed by ASD (Ref 5).

SAM Fire Analyzer Model

The SAM Fire Analyzer was developed by Rockwell for the Naval Air Development Center. The program has evolved from a simple, straight and level, purely geometric calculator to a compact model that considers doctrine, ECM, and cumulative PK. All discussion will be based on the more advanced form of the model.

This model is based on a SAM site located at the origin of a three dimensional Cartesian coordinate system. Aircraft pass the site flying perpendicularly to the defined Y-axis. Velocity and altitude are constant, and the flight path is straight and level. Missile trajectory played by Fire Analyzer is approximated as a straight line collision course. The use of the aircraft and missile velocities provides points of fire and the position of the aircraft at those points. Given these points, the model finds the maximum number of launches (or shots, for AAA) and the number of those that will be successful.

Some of the specific capabilities of the Fire Analyzer Model are:

1. Consideration of an initial time delay for acquisition, track, evaluation, lock-on, warm-up, and decision to fire (first fire only).

2. Consideration of a time delay between shots, from assessment of damage from last intercept to the next launch. This implies a shoot-look-shoot firing doctrine.

3. Evaluation of geometric intercept envelope.

4. Consideration of missile performance in Doppler dead zone, with and without memory capability. If memory does exist, memory limits are played.

5. Consideration of intercept occurring in the Doppler dead zone and inclusion of a time delay to reacquire the aircraft upon emergence from the dead zone.

6. Evaluation of minumum and maximum angles of fire.

7. Modeling a ripple-fire doctrine instead of a shoot-look-shoot doctrine.

8. Identification and rejection of clutter.

9. Consideration of the maximum radial velocity of the target at which lock can be maintained.

10. ECM calculations include aspect angle, RCS, CEP, J/S, PKSS, and cumulative PK.

The output that the model provides includes:

1. Echo print of input.

2. Aircraft flight path, velocity and altitude.

3. Number of shots taken and PKSS for each, tabulated by offset.

4. Aircraft survival and kill probabilities, tabulated by offset.

5. Effective radius of site.

6. Maximum PK for all offsets.

7. Integrated PK.

8. Site random kill and random survival probability.

The level of resolution of this model is not tremendously deep, nor are the assumptions very complex. The model itself is simple. For quick, rough estimates that do not require extreme accuracy, this model is a good tool: fast and relatively small.

GENSAM

The Generic Surface-to-Air Missile Model, GENSAM, was developed by the Caywood-Schiller Division, A.T. Kearney, Inc. and the Joint Technical Coordinating Group/Aircraft Survivability and delivered to the Naval Air Development Center in October 1981. GENSAM was designed to evaluate the survivability of generic aircraft systems facing generic SAM threats. The evaluation is accomplished by calculating aircraft performance, missile launch opportunities, missile fly-out performance and intercept conditions based on user-supplied parameters. The aircraft-missile system evaluation occurs in as realistic a manner as possible, given the need for simple input and short running time.

There are three frames of reference which interplay in the model. One refers to velocities and positions in terms of an arbitrarily established ground inertial coordinate system. The second frame is that of the relative wind system. This system is a right-handed

system nearly identical to the first system; but the origin is displaced to the center of gravity of the aircraft, and the X axis is defined by the aircraft's velocity vector. The third system is defined by the pitch, yaw, and roll axes of the aircraft. These three systems are related to each other through Jacobian transformation matrices and in the model in clear and convenient terms.

A defensive unit is located in inertial space, and an incoming attacker flies a pre-determined flight path past or over the site. The SAM site can detect and track targets, evaluate launch requirements, and launch missiles which attempt to intercept the aircraft. The aircraft may or may not detect the SAM emissions and then may choose to employ ECM, decoys, or evasive maneuvers.

GENSAM utilizes a construct called the information state of the system to determine what phase of engagement the simulation is in. Unique codes define what types of sensors are being used, if ECM is being used, whether or not detection or tracking exists, and the launch status. The information state is determined at each time step and determines the next action to be taken. Events and decisions that may occur for the aircraft are:

1. Detection of hostile surveillance radar.
2. Initiation of surveillance radar jamming.
3. Detection of hostile track radar.

4. Initiation of track radar jamming.

5. Detection of missile launch.

6. Launch of decoys.

7. Initiate evasive maneuvers.

The defensive site may:

1. Detect hostile aircraft.

2. Assign tracking radar.

3. Track targets.

4. Assign a launcher.

5. Be within or outside of launch limits.

6. Launch a missile.

7. Assign guidance mode.

The data needed for these events or decisions to occur in the model includes:

1. Target signature data, radar and/or IR.

2. Emitter and sensor data on the target.

3. Emitter and sensor data on the defense.

4. Target flight path in the form of turnpoints.

5. Defense range, slewing (rate of movement of gun aimpoint), elevation, seeker, and LOS limits.

6. Detection, search-to-track, and launch delay times.

7. Atmospheric data and aircraft flight parameters.

Given that a launch does occur and the aircraft is aware of the launch, the aircraft may begin evasive

maneuvers. The GENSAM algorithm:

1. Determines the appropriate action: random jinking, maximum g turn, steep dive, evasive climb, or chandelle.

2. Determines the forces and aircraft orientation required by this action.

3. Compares the required forces and orientations to the limits of the aircraft and pilot.

4. Determines the best compromise between required and limiting forces. The resulting velocity vector and orientation angles are given to the equations of motion. The equations of motion are integrated linearly by time pulse.

This process continues until the missile velocity drops below required velocity for flight, the missile exceeds maximum range, the missile goes below its minimum altitude, the missile time of flight exceeds maximum time of flight, the missile range from the aircraft equals range of closest approach (fuzing), guidance is terminated due to excess range between target and receiver, or the J/S exceeds the critical J/S.

Fuzing occurs when the right circular cone which constitutes the fuzing pattern of the missile intersects a glitter point of the target. If the fragment spray pattern from the fuzing point (burst point) intersects the target, the probability of kill is computed. PK is calculated based on a circular normal distribution of

missile trajectory about the target and a given lethal radius of the weapon on the target.

$$PK = R^2/C^2\, e^{-d^2/C^2}$$

R is the lethal radius, obtained from table look up with the weapon type and aircraft. D is the approach distance of the missile to the target, and

$$C = R^2/2 + 2*\ln(CEP)^2$$

The terminal encounter conditions, approach azimuth, elevation, and velocities can be stored and submitted to an off-line routine for more rigorous evaluation. Another on-line analysis tool exists. It is the Conceptual Vulnerability Assessment (CVA) model, developed by Millard C. Mitchell and Paul Young (Ref 12). The CVA model calculates the vulnerability of aircraft to detonations of non-nuclear proximity fuzed guided missile warheads.

Other capabilities or incorporations of interest in GENSAM are:

1. Vulnerable areas of the aircraft are classed as:

   -Components which do not change in presented area.

   -Components for which the area presented is directly proportional to the square of the wing loading.

-Components for which the area presented is directly proportional to the gross weight of the aircraft raised to the 2/3 power.

-Component whose presented area is directly proportional to the wing area.

2. The look-up tables that provide the PKSS are entered with component class, aspect angle, fragment mass and fragment velocity.

3. ECM is played as noise or deception. Standard radar range equations are utilized.

4. Missile fly out is by proportional navigation, pursuit course, or beam rider, as appropriate.

GENSAM is a relatively high resolution model. The treatment of acquisition, track, break lock, ECM, aircraft performance, fly out, fuzing and probability of kill are all calculated fairly accurately for the one on-one-case. GENSAM is preferred over Fire Analyzer for precise insights to the problem.

MICE II

The MICE II (Missile Intercept Capability Evaluation) model was developed by Vought Corporation in 1977 for the Joint Technical Coordinating Group on Aircraft Survivability, and Aeronautical Systems Division. The model is a five degree of freedom simulation of an engagement between a SAM and its target. The simulation

is written in FORTRAN IV for implementation on the CDC 6600. MICE plays six SAM systems, four radar and two IR. The methodology includes calculation of target lock-on range, target PK, masking, noise jamming, and intercept range.

The aircraft in MICE flies a prespecified fight path, but has one alternate flight path that can be switched over to during flight. The events and decision points in MICE are:

1. Initialize engagement conditions from model inputs.
2. Read in or generate target flight path.
3. Check for lock-on conditions (evaluates radar range, jamming, etc.).
4. Check SAM launch requirements.
5. Launches, and generates SAM guidance commands.
6. Flight path history is constructed from guidance commands.
7. Checks engagement's termination conditions.
8. Calculates target miss distance.
9. Calculates target PKSS and cumulative PK.
10. Launches next missile or terminates simulation.

There are two coordinate system frames of reference used in MICE. The first is an arbitrary inertial system used to define the target location. The second is a stability reference system with origin at the center of

mass of the missile. The X axis for this system is the missile's velocity vector, the Y axis is the yaw axis, and the Z axis is mutually perpendicular. A direction cosine matrix allows for conversion from one system to the other.

Missile trajectory is generated through the use of equations of motion, launch parameters, and missile performance parameters. Integration of the equations of motion is done through linear approximation (slope averaging) at small time increments. The quantities included in the equations of motion and associated performance parameters are linear acceleration, attitude angle turn rate, azimuth angle turn rate, thrust, weight, lift, drag, guidance type (proportional navigation), command guidance smoothing, and engagement termination criteria.

For the SAM to launch, line of sight range from the site to the target must not exceed the maximum target lock-on range of the seeker or the masking range (determined by terrain and clutter, or the radar multipath angle). The line-of-sight range must also be less than the maximum range of the missile.

The engagement terminates when certain combinations of conditions exist. The individual criteria are:

1. The range from launcher to aircraft exceeds some maximum.

2. The range from missile to aircraft exceeds

some maximum.

3. The break track time exceeds some maximum.

4. The seeker look angle exceeds one half of its look angle limit.

5. The target range exceeds the target closing distance in some time interval.

6. The angular tracking rate exceeds the allowable tracking rate.

7. The missile velocity falls below a required minimum intercept velocity.

Aircraft trajectory is provided through the input of a precalculated trajectory or the input of a flight path from which the trajectory is generated. The flight is specified through definition of elapsed time into flight, X,Y,Z position, velocity, pitch angle, roll angle, heading, attack angle, and sideslip angle. The flight parameters necessary to calculate the trajectory are aircraft velocity, acceleration, deceleration, vertical g equilibrium, vertical g maximum, vertical deceleration with g maximum, horizontal g equilibrium, horizontal g maximum, and horizontal deceleration with g maximum.

At certain points in the aircraft trajectory, a second flight path may be inserted in place of the original. This second path is defined relative to the positions of the first and must occur at an already defined time point of the first path. This capability

provides the analyst with some on-line tactical decision making flexibility but is highly sensitive to errors in timing and heading.

Target kill probability can be determined through table look-up, or calculated. The look-up requires the missile's miss distance to index the PKSS value. The calculation of PK is done as in TERRAIN with the identical CEP equation and PK calculations for the with and without ECM cases. Cumulative PK values are also tracked.

MICE is a fairly small, quick running, medium resolution model of SAM engagements. The modeling of the MICE aircraft's aerodynamics is not at quite as high a level of resolution as is GENSAM's, but the model logic is simpler to understand and the simulation runs slightly faster. The capabilities of MICE and GENSAM are roughly equal. A choice between the two depends on the analyst's preferences.

ADADS

The ADADS (Air Defense Artillery Defense Suppression) Model was developed within Tactical Air Command by the Joint Studies Group. The model is an event-driven simulation of any number of aircraft on any number of defenses. The simulation is written in FORTRAN IV for implementation on the CDC CYBER 74. ADADS plays two-sided conflict. ADU sites are displayed about maneuver unit

positions in the simulation as specified in the data base. The site is oriented with respect to an X,Y,Z grid.

ADADS is based on a ground scenario specified in the model data base. Each side, red and blue, has maneuver units positioned on the X,Y grid. Maneuver units have ADU sites which are deployed about the owning unit according to the deployment grid in the data base. The grid is oriented according to the owning unit. Red units have their Y axis aimed in the direction the maneuver unit is moving (or last moved if currently stationary). Blue units have their Y axes aimed in the direction from which they expect the enemy to attack.

There are seven basic types of air defense units in ADADS. They can be characterized by their lethal envelope descriptions:

1. Front half of ellipse with major axis parallel to Y axis orientation. Shoots at approaching targets.

2. Back half of ellipse with major axis parallel to Y axis orientation. Shoots at receding targets.

3. Full ellipse with major axis parallel to Y axis orientation. Shoots at approaching and receding targets.

4. Front half of ellipse with minor axis parallel to Y axis orientation. Shoots at approaching targets.

5. Back half of ellipse with minor axis parallel to Y axis orientation. Shoots at receding targets.

6. Full ellipse with minor axis parallel to Y axis

orientation. Shoots at approaching and receding targets.

7. A pie-shaped wedge formed from the intersection of two lines radiating from the defense site location with some angle between them and a circle of given lethal radius about the site. The wedge is oriented along the Y axis of the site and shoots at any aircraft in its area.

The lethal envelopes were broken down into these categories to reflect as accurately as possible the different types of ADU's deployed and the manner in which they are oriented.

Each deployed site has a maximum and minimum range (lethal zone), probability of being operational, and a statistically computed acquisition range. The acquisition range is calculated from a terrain masking algorithm. A random draw is made to determine the radius of the acquisition circle given a mean radius μ and a variance σ. The radius is defined as

$$\mu + X\sigma > R > \mu - Y\sigma$$

where X, Y, μ, and σ are defined in the data base. Aircraft flying outside this circle, above the maximum detection altitude, or below the minimum detection altitude maintain mask. The probability of a site being operational is based on the ADU type and status of the

owning unit (moving, stationary, under repair, etc.).

The firing doctrine of the sites is shoot-look-shoot. This can be changed by the communication status of the site. ADADS plays site netting, either autonomous or non-autonomous. Two non-autonomous sites will never engage the same target at the same time. After each shot, the opportunity to hand the target over to another site with a better shot is evaluated. Autonomous sites do not become involved with these evaluations and do not affect the outcomes for the netted units.

Aircraft flight paths are input through a fixed data base. This data base contains X,Y,Z coordinates on a UTM grid, velocity, and heading. Initiation of flight, turn point, altitude or velocity change, intersection with a SAM acquisition envelope, exiting a lethal envelope, or flight path termination constitute model events scheduled by aircraft action. At event times, launch opportunities and precedence of fire criteria are evaluated. If launch occurs, probability of damage and probability of kill are calculated. These values are derived by generating random numbers and using using them as indices in a table look up.

As the simulation progresses, count is kept on the cumulative damage on each aircraft, the cumulative PK, the number of missiles by rail, TEL, and site, and the required reloads.

The surface-to-air attrition is played for red and blue. ADADS also incorporates an examination of blue's suppression of red's air defenses. Defense suppression is carried out by:

1. Actually scheduling a defense suppression mission.

2. Diverting an aircraft on some other mission to carry out SEAD (suppression of enemy air defense).

3. A homeward bound flight finding a target of opportunity.

Defense suppression requires that the unit that owns the ADU be acquired by the aircraft and the aircraft must be carrying an emitter tracking or equivalent load. The aircraft makes as many passes against the ADU target as possible, and effectiveness is calculated through table look-up, based on the number and characteristics of the passes that occurred. Effectiveness is tracked as the number and kinds of vehicles destroyed and cumulative probabilities of kill. As the blue aircraft is making passes against the red site, it is vulnerable to attack. Blue aircraft attrition and PK are calculated along with red ADU attrition and PK.

ADADS also plays defense suppression through the use of harassment vehicles. Harassment vehicles are drones that are launched into the enemy's air defense zone and loiter, seeking, and attempting to destroy any ground

emitter onto which it can lock. Harassment occurs in two ways.

The first is by a harassment event. Harassment vehicles are loitering in an area searching for sites that are blinking on and off. If a radar is blinked on and stays on for a sufficient length of time to be locked on to, the harassment vehicle will dive at the site in an effort to destroy it. The harassment vehicle may not remain locked-on long enough to enter the terminal phase of its dive. If lock is broken, the vehicle will move the centroid of its loiter area to the point where lock was broken, climb back to altitude, and continue to loiter and seek.

Given that the harassment vehicle does remain locked on and in the course of its dive goes below its commitment altitude, it will continue whether or not the site blinks off. If the site remains up, the seeker will continue to update its course until it gets so close that the ADU site's emissions burn out the seeker head. At that point the vehicle's trajectory becomes ballistic. The vehicle's trajectory also becomes ballistic if, after passing commitment altitude, the ADU emitter blinks off and does not blink back on.

The second method of accomplishing harassment is basically a function of the first and differs more in philosophy than effect or method. If the harassment

vehicle locks-on to an ADU site that is engaged with a friendly aircraft, the site will either be forced to shut down for self-preservation or be killed. In either event, the aircraft previously engaged no longer faces a threat.

PK of an ADU site attacked by a harassment vehicle is a function of weapon, ADU type, and the altitude at which blink off occurred. PK has a linear increase with decrease in altitude. The limiting factor is burn out altitude of the seeker head.

ADADS addresses the standard question of attrition of egressing aircraft from a much more aggregate level than the models previously discussed. PK values are determined in higher resolution models (typically TAC ZINGER) and supplied to ADADS for table look-up. The area of acquisition range is treated statistically. Many of the quantities for P_D, PK, acquisition range, etc. are determined stochastically. One-on-one engagements can be played as easily and accurately as one-on-many or many-on-many engagements. For high resolution studies and conclusions, this model might not be the best tool available but for an overall impression of the surface-to-air battle as well as the air-to-surface battle and effects of SEAD and harassment, ADADS offers much that is not available elsewhere. Validation of ADADS appears to be minimal. That fact should be weighed carefully before utilizing the model.

Current Developments

There is a large community within DoD concerned with SAM and AAA effectiveness and aircraft vulnerability. HQ USAF, Tactical Air Warfare Center, Aeronautical Systems Division, Tactical Air Command, and many smaller military and civilian organizations have studied this problem and developed models and methodologies. These models and methodologies range from the short, simple, analytic models to large, detailed, time-intensive simulations and families of simulations.

The most widely used and accepted model of AAA in use within DoD is P001 (Ref 19). P001 computes the probability of kill of a target aircraft flying a pre-defined flight path through user-selected and positioned artillery (Ref 2:28).

The SAM equivalent to P001 is TAC ZINGER (Ref 9). ZINGER is a group of models that addresses different Warsaw Pact SAM's, SA-2 through SA-12. The ZINGER models are written in FORTRAN IV. They were originally implemented on the Honeywell 6635 MULTEX computer at AF Studies and Analysis but have been converted for operation on IBM, CDC, and UNIVAC systems.

In the course of development of the different ZINGER models, code was written for each specific SAM, tested, and used separately. Later, when all the modules were

completed, they were grouped together and reorganized.

Each ZINGER model consists of a main program and from four to eleven subroutines specific to SAM type. There are, additionally, some forty other subroutines required commonly by all SAM models. The common use subroutines were rewritten and condensed.

The main program controls the overall progress of the simulation. Input, output, data print back, and initializations occur here. Run parameters for the missile and guidance are specified by namelist. A flight path can be generated externally by the BLUE MAX program and read in, or a straight and level flight path can be generated internally. Use of BLUE MAX is time-intensive but very precise. BLUE MAX is a specifically designed, interactive, front-end tool for ZINGER. Data must also be provided on the defensive site, target signature values, antenna patterns, and terrain data. ZINGER's are capable of handling up to 200 sites. The main program examines the flight path at discrete time intervals, checks all defensive sites, determines launch conditions, simulates the missile flyout from those sites that launch, and calculates PK. ZINGER is designed so that sensitivity analysis on parameters is especially easy. The program can execute, recycle, change parameters, execute, etc.

The ZINGER models consider SAM's individually by type so not all models possess the same capabilities. The

areas that are addressed (in whichever model is appropriate) include:

1. Derivation of target and missile positions from integration of equations of motion.

2. Assessment of mask areas.

3. Assessment of multipath effects.

4. Look up of target signature and IR attenuation based on range.

5. Generation of appropriate guidance commands.

6. Calculation of probability of hit and probability of kill based on the contact hit or proximity fuzing submodels, blast and/or fragment flyout submodels, missile reliability, miss distance, and the target's presented and vulnerable areas.

7. Five degree-of-freedom guidance. A Runga-Kutta starting routine feeds an Adams-Moulton numerical integration routine. The commanded accelerations in pitch and yaw are calculated through a second-order flight control system from the given position and LOS angular rate of both the target and missile.

8. Maximum tracking rate, acceleration, and gimbal limits of the missile (SA-8).

9. Evaluation of guidance commands and aerodynamic constraints to determine position update.

10. Generation of position, velocity and intensity of flares.

11. First-order time lag in missile reaction to guidance.

12. Signal and signature degradation for helicopters.

13. Probability of kill due to blast and pellet flyout to the center of gravity of the individual critical components.

14. Probability of kill based on the representative component's length in the fragmentation spray.

15. Adjustment for elevation biases.

16. Optical tracking, including acquisition of low altitude targets.

17. Ground axis system and inertial axis system.

18. Rectangular and circular site arrays.

19. Premature fuzing off of ground clutter.

20. Wobulation jammer sub-simulation.

The required inputs mentioned above, specifically the missile characteristics and performance data, come from Defense Intelligence Agency manuals. It follows that ZINGER, the data, code and results, are classified. Running on a classified mainframe presents certain logistical problems, but those must be borne when using a model of such high resolution and precision.

Run times are from 5 seconds to 30 hours of CP time depending on the complexity of the threat array, the length of the flight path, the length of the model's time steps, and the amount of sensitivity analysis on the model

parameters.

It may be noted that ZINGER incorporates virtually all of the features of the models previously mentioned. The modeling of all these areas at the same time and at the correct relative levels of resolution is what makes ZINGER the number one SAM model in DoD.

P001 and the ZINGER models are combined in TAC REPELLER (Ref 2:ii-47) which investigates few-on-few engagements in detail. REPELLER models aircraft movement along pre-specified fight paths, threat detection, theat prioritization (by radar signature), target selection by ADU units, engagement, defense suppression, missile seeker dynamics, ECM, guidance dynamics, missile kinematics, and proximity fuzing (Ref 8:32). The jamming and ECM that is played occurs within the ZINGER models. In general, any question specific to a particular SAM type is best answered by ZINGER with REPELLER handling the aggregate modeling. REPELLER, with its components, represents the most sophisticated analytic tool for studying SAM-aircraft interactions.

Much work has been done in the area of SAM modeling, and it is continually being updated. Fairchild is in the process of building a TF flight path generator that will be integrated with TAC ZINGER (Ref 14). This capability is projected to be available in late 1982.

The following list gives a brief idea of how many

credible, useful SAM models (simulation or analytic type) exist.

EVADE II	TACOPS	COMO	NORSAM
MASKPAS	APEP	ITEM	DSAM
SIMFIND	FIRE	SAMEN	SADS
MIA	AGGRESSOR	ATTACKER	TACOS

Additional references and guides to models are available in the TAC Catalog of S/A and Gaming Models (Ref 8), Catalog of EW Computer Models and Programs (Ref 2), and the Catalog of War Gaming and Military Simulation Models (Ref 13).

Appendix B

Model Attributes Comparison Chart

	MODIFIED TERRAIN	FIRE ANALYZER	GENSAM	MICE II	ADADS	ZINGER	POO1
PROGRAM USE							
DESIGN MODIFICATION							
FORCE STRUCTURE DECISION					X	X	
SYSTEM/SUBSYSTEM EVALUATION	X	X	X	X	X	X	X
TACTICS DEVELOPMENT	X	X	X	X	X	X	X
PROGRAM CHARACTERISTICS							
AIR-TO-SURFACE					X		
SURFACE-TO-AIR	X	X	X	X	X	X	X
ONE-ON-ONE	X	X	X	X	X	X	X
ONE VS MANY	X				X	X	X
MANY VS MANY					X	X	X
TWO SIDED					X		
TERRAIN DESCRIPTION	X				X	X	
LANGUAGE (a)	F	F	F	F	F	F	F
PROGRAM SIZE (b)	S	S	S	M	L	L	M
PORTABLE (c)	S	T	S	S	S	T	T
AIRCRAFT CHARACTERISTICS							
MANEUVERABILITY			X	X	X	X	
VULNERABLE AREA (d)	T	T	T	C	T	T	T
IR SIGNATURE	X		X	X	X	X	
RCS SIGNATURE	X	X	X	X	X	X	
OPTICAL SIGNATURE			X		X	X	
ON BOARD ECM	X	X	X	X	X		
AIRCRAFT WEAPONRY							
TYPES				X			
TRAJECTORIES				X			
ACCURACY				X			
PK'S				X			

	MODIFIED TERRAIN	FIRE ANALYZER	GENSAM	MICE II	ADADS	ZINGER	POO1
GROUND WEAPON CHARACTERISTICS							
WEAPON DISPERSION (e)	M	1	M	1	M	M	M
NUMBER OF SHOTS (f)	S	1	1	S	S	1	S
FIRING DOCTRINE	X	X	X	X	X	X	X
ROUND LIMITATIONS	X	X		X	X	X	X
REACTION TIME	X	X	X	X	X	X	X
TYPE TRACKING (g)	R	R	B	R	R	R	B
TRACKING LIMITS	X	X	X	X	X	X	X
ERROR CONSIDERATIONS						X	X
LINEAR PREDICTION	X	X	X	X	X	X	X
PROJECTILE PERFORMANCE	X					X	X
INTERCEPT COMPUTATION	X	X	X	X	X	X	X
MISSILE PERFORMANCE							
SPEED	X	X	X	X	X	X	
ACCELERATION			X	X	X		
G LOADING	X		X	X	X		
WEAPON LOCATION	X				X	X	X
MASK DATA	X			X		X	X
RULES OF ENGAGEMENT					X	X	X
DETECTION MODELING							
ACOUSTIC							X
INFRARED	X		X			X	
OPTICAL/VISUAL			X				X
RADAR	X	X	X	X	X	X	X
METEOROLOGICAL EFFECTS					X		

	MODIFIED TERRAIN	FIRE ANALYZER	CENSAM	MICE II	ADADS	ZINGER	POO1
PROGRAM OUTPUT							
INPUT DATA PLAYBACK	X	X	X	X	X	X	X
FLIGHT PATH EVENT HISTORY							
MASKING STATUS	X						
ALTITUDE PROFILES	X	X		X		X	X
AIRCRAFT WITHIN EFFECTIVE RANGE	X		X		X	X	X
AIRCRAFT RECEIVES FIRE	X	X	X		X	X	X
AIRCRAFT RETURNS FIRE					X		
PKSS	X	X	X	X	X	X	X
CONTINUOUS PK	X	X		X	X	X	X
ATTRITION POINT					X	X	X
GROUND WEAPON EVENT HISTORY							
DETECTION OCCURRENCE	X	X	X	X	X	X	X
MASK STATUS	X						
AIRCRAFT WITHIN EFFECTIVE RANGE	X	X	X	X	X	X	X
FIRING RECORD	X	X	X	X	X	X	X
RECEIVES FIRE FROM AIRCRAFT					X		
GROUND WEAPON PK					X		

LEGEND

(a) F = FORTRAN
S = SPECIAL PURPOSE LANGUAGE
O = OTHER LANGUAGE

(b) L = LARGE, MORE THAN 200K
M = MEDIUM, 100-200K
S = SMALL, LESS THAN 100K

(c) N = NOT PORTABLE
S = SEMI-PORTABLE
T = TOTALLY PORTABLE

(d) C = COMPONENT AREAS
T = TOTAL AIRCRAFT

(e) 1 = ALL AT ONE SITE
M = SPREAD AMONG MULTIPLE SITES

(f) 1 = SINGLE SHOT
S = SALVO

(g) O = OPTICAL
R = RADAR
B = BOTH

Appendix C

TERRAIN User's Guide

Very little internal documentation exists in the TERRAIN code, and there is absolutely no external documentation. The lack of documentation in the code hinders the analyst but does not affect the user since his attention never reaches the coding level. The user is affected though by the absence of any kind of formal or informal written explanation of the model and/or how to run it. The purpose of this chapter is to provide a summary of the hardware and software requirements to run the program and then a step by step guide on how to execute the model.

Model Operation

The model runs mainly in an interactive mode, which requires a graphics terminal, but a modification for batch operation has been developed. The graphics package in use is designed for TEKTRONIX machines. Operation at less than 1200 baud is not recommended due to the length of time to present some of the graphical output.

TERRAIN exists as an absolute binary module. An absolute module is object code that contains all the external references, subroutine calls, and library functions that a program needs to execute all in one

package. No other libraries or binaries are required.

TERRAIN does require four specific data files to execute. These files contain information on the defense locations, aircraft flight performance characteristics, the digitized terrain data, and the road and political boundary locations. The user may include three additional files produced by prior runs of the model. The ability to utilize old data files provides TERRAIN with a "restart" capability. The restart data files contain information on the aircraft's terrain-following flight path, the altitude of the aircraft's flight path, the altitude of the terrain under the flight path, and the aircraft's line of sight data (the defensive sites that could see or be seen by the aircraft). The availability of this data eliminates the need to specify the same flight path and parameters between successive runs and saves a great deal of time.

Figure C-1 presents the procedure that attaches the necessary files and invokes the TERRAIN absolute. The first line provides the user with the data file flexibility mentioned above. The TAPEx parameters in the procedure call specifies which data files are to be attached as specified in the CYBER Control Language (CCL) of the procedure and which are to be obtained from some alternate disk file.

```
.PROC,TERRAIN,TAPE1-NO,TAPE2-NO,TAPE3-YES,TAPE4-NO,
 TAPE7-YES,TAPE8-YES,TAPE10-YES,ID-TERRAIN,CY-10.
CONNECT,INPUT.
CONNECT,OUTPUT.
IFE,$TAPE1$.EQ.$YES$,IFT1.
RETURN,$TAPE1.
ATTACH,T1,ZUSXY,$ID-ID,SN-ASDAD.
REWIND,T1.
COPYBF,T1,$TAPE1.
RETURN,T1.
ELSE,IFT1.
IFE,$TAPE1$.NE.$NO$,IFT1.
RETURN,$TAPE1.
ATTACH,T1,TAPE1,$ID-ID,SN-ASDAD.
REWIND,T1.
COPYBF,T1,$TAPE1.
RETURN,T1.
ENDIF,IFT1.
IFE,$TAPE2$.EQ.$YES$,IFT2.
RETURN,$TAPE2.
ATTACH,T2,HUSXY,$ID-ID,SN-ASDAD.
REWIND,T2.
COPYBF,T2,$TAPE2.
RETURN,T2.
ELSE,IFT2.
IFE,$TAPE2$.NE.$NO$,IFT2.
RETURN,$TAPE2.
ATTACH,T2,TAPE2,$ID-ID,SN-ASDAD.
REWIND,T2.
COPYBF,T2,$TAPE2.
RETURN,T2.
ENDIF,IFT2.
IFE,$TAPE3$.EQ.$YES$,IFT3.
RETURN,$TAPE3.
ATTACH,T3,DEFLOC,$ID-ID,SN-ASDAD.
REWIND,T3.
COPYBF,T3,$TAPE3.
RETURN,T3.
ELSE,IFT3.
IFE,$TAPE3$.NE.$NO$,IFT3.
RETURN,$TAPE3.
ATTACH,T3,TAPE3,$ID-ID,SN-ASDAD.
REWIND,T3.
COPYBF,T3,$TAPE3.
RETURN,T3.
ENDIF,IFT3.
IFE,$TAPE4$.EQ.$YES$,IFT4.
RETURN,$TAPE4.
ATTACH,T4,ACLOS,$ID-ID,SN-ASDAD.
REWIND,T4.
COPYBF,T4,$TAPE4.
RETURN,T4.
ELSE,IFT4.
IFE,$TAPE4$.NE.$NO$,IFT4.
RETURN,$TAPE4.
ATTACH,T4,TAPE4,$ID-ID,SN-ASDAD.
REWIND,T4.
COPYBF,T4,$TAPE4.
RETURN,T4.
ENDIF,IFT4.
IFE,$TAPE7$.EQ.$YES$,IFT7.
RETURN,$TAPE7.
ATTACH,T7,ACEQ,$ID-ID,SN-ASDAD.
REWIND,T7.
COPYBF,T7,$TAPE7.
RETURN,T7.
ELSE,IFT7.
IFE,$TAPE7$.NE.$NO$,IFT7.
RETURN,$TAPE7.
ATTACH,T7,TAPE7,$ID-ID,SN-ASDAD.
REWIND,T7.
COPYBF,T7,$TAPE7.
RETURN,T7.
ENDIF,IFT7.
IFE,$TAPE8$.EQ.$YES$,IFT8.
RETURN,$TAPE8.
ATTACH,T8,GB1,$ID-ID,SN-ASDAD.
REWIND,T8.
COPYBF,T8,$TAPE8.
RETURN,T8.
ELSE,IFT8.
IFE,$TAPE8$.NE.$NO$,IFT8.
RETURN,$TAPE8.
ATTACH,T8,TAPE8,$ID-ID,SN-ASDAD.
REWIND,T8.
COPYBF,T8,$TAPE8.
RETURN,T8.
ENDIF,IFT8.
IFE,$TAPE10$.EQ.$YES$,IFT10.
RETURN,$TAPE10.
ATTACH,T10,GBIRDS,$ID-ID,SN-ASDAD.
REWIND,T10.
COPYBF,T10,$TAPE10.
RETURN,T10.
ELSE,IFT10.
IFE,$TAPE10$.NE.$NO$,IFT10.
RETURN,$TAPE10.
ATTACH,T10,TAPE10,$ID-ID,SN-ASDAD.
REWIND,T10.
COPYBF,T10,$TAPE10.
RETURN,T10.
ENDIF,IFT10.
IFE,FILE(TERRAIN,.NOT.AS),IFTT1.
ATTACH,TERRAIN,$ID-T820214,SN-ASDAD,$CY-CY.
ENDIF,IFTT1.
TERRAIN.
RETURN,$TAPE3,$TAPE7,$TAPE8,$TAPE9,$TAPE10.
RETURN,TERRAIN.
REWIND,TAPE6.
DISCONT,OUTPUT.
COPYEF,TAPE6,OUTPUT.
REWIND,OUTPUT.
RETURN,TAPE6.
```

Program Initiation and Description of Options

Line 2110 in the procedure file actually begins the program, and the seven lines following the invocation prepare the results for outputting after program termination. When the program is invoked, the graphics environment is initialized, and the TERRAIN master menu (Figure C-2) is displayed.

```
TERRAIN MASTER MENU
(1) STOP
(2) ZCUT, CONSTANT ALTITUDE CUTS (2,0)&(3,0)
    ENTER: 2,ALTITUDE(METERS)
                                OR ABOVE, 1 FOR PTS ABOVE
                                OR ABOVE,-1 FOR PTS BELOW
(3) ZVIEW, TERRAIN VISIBLE TO A/C (4,0)&(5,0)
    ENTER: 3,X(METERS),Y(METERS),A/C CLEARANCE(FT)
                                OR ABOVE, 1 FOR PTS ABOVE
                                OR ABOVE,-1 FOR PTS BELOW
(4) ZVSXY, GROUND PATH & TERRAIN Z (10,0)
(5) HVSXY, A/C PATH & RESULTING H (11,0),(12,0),(13,0)
    (1) MODIFY RADAR/AIRCRAFT PARAMETERS
    (2) GENERATE TERRAIN FOLLOWING DATA
        (1) A/C $1
        (2) A/C $2
        (3) A/C $3
        (4) A/C $4
        (5) A/C $5
        (6) OTHER
        (99)COMPUTE PATH(CURRENT A/C)
    (3) TERRAIN FOLLOWING PLOTS
    (4) TERRAIN ANALYSIS
    (5) CLEARANCE ANALYSIS
(6) TVIEW, A/C PATH/DEFENSE LOS
(7) DVIEW, DEFENSE LOS COVERAGE
    ENTER: 7,X,Y,DZ DEF (METERS), A/C DH(FEET)
(8) DVIEW(TAPE3), DEFENSE LOS COVERAGE
    ENTER: 8,A/C DH(FEET)
INPUT OPTION (AND SUB-OPTS IF REQD):
```

Figure C-2

There are eight options, the first of which is to exit the program. This then cleans up the data files and prepares the output for printing. Option 2 allows the user to examine the terrain relief for the entire sector and look for all the points at, above, or below a specified altitude. This provides information on how to go about planning a mission and specifying the flight path. By inputting 2,600, the display shown in Figure C-3 is generated. All the points at exactly 600 meters above sea level (ASL) are displayed. Inputting 2,300,-1 displays all the points at or below 300 meters ASL (Figure C-4), and 2,700,1 displays the points at or above 700 meters ASL (Figure C-5).

Option 3 allows the user to specify an X,Y coordinate location for the aircraft and the aircraft's clearance above that X,Y point in feet. The terrain that is visible, not masked, to the aircraft at this point is generated and displayed in Figure C-6. The Figure C-6 output is produced in response to input of 3,95000,25000,200. This output can be subdivided into plots of the terrain seen above and below the specified aircraft altitude. Input of 3,95000,25000,200,1 produces Figure C-7, the terrain points visible to the aircraft at or above the aircraft altitude. Input of 3,95000,25000,200,-1 produces the at or below plot in Figure C-8.

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
H= 600 M PTS AT H

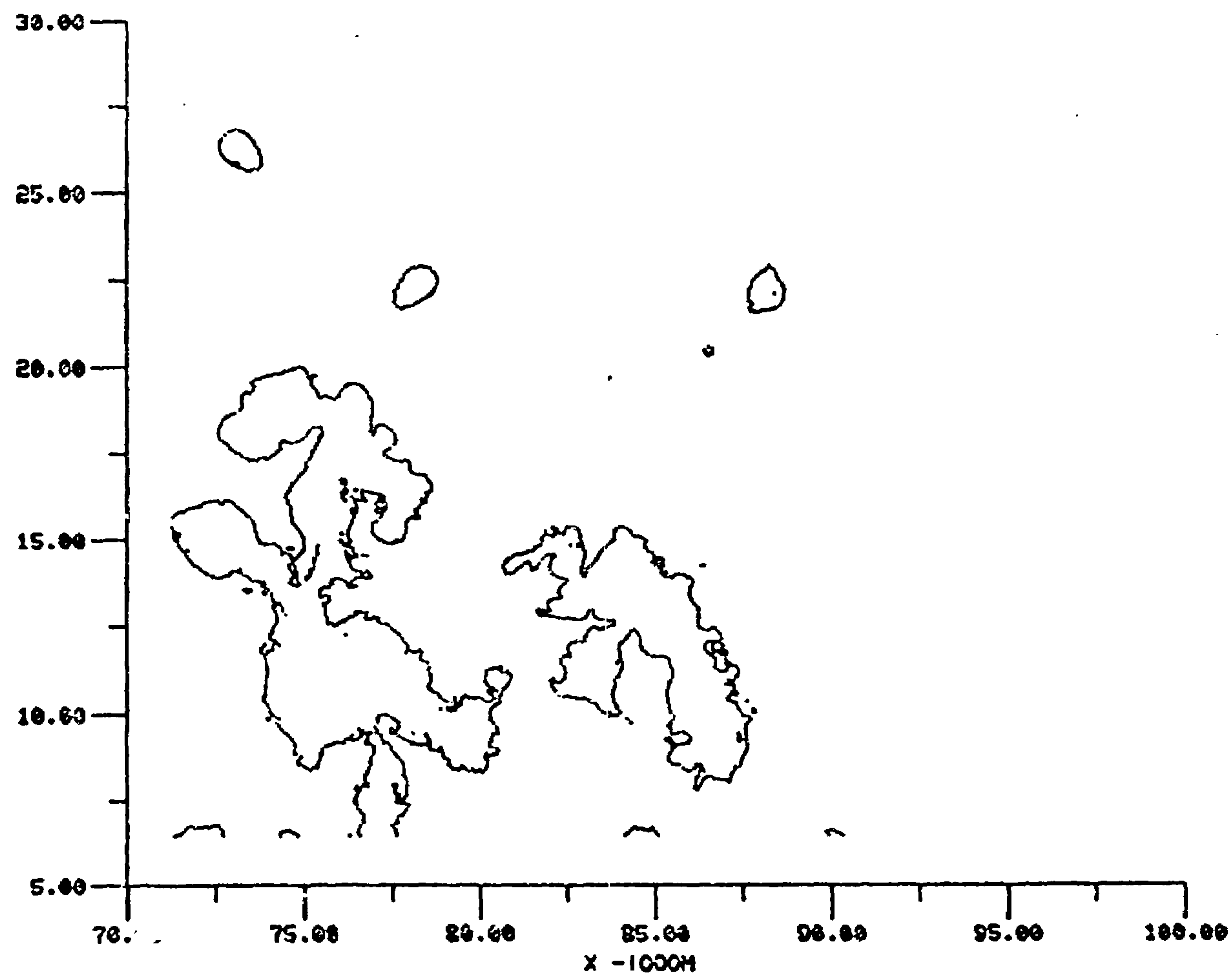


Figure C-3

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
H= 300 M PTS BELOW

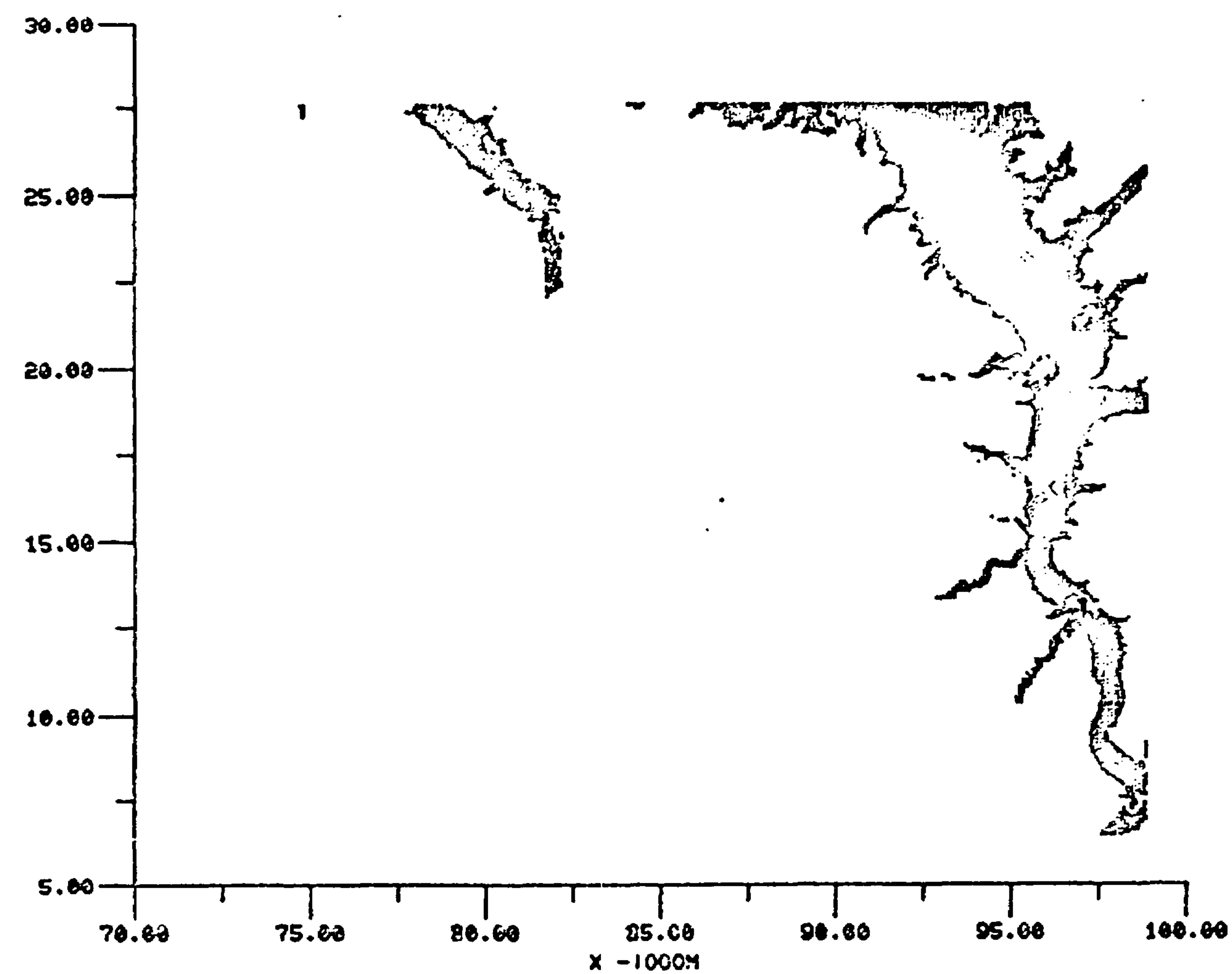


Figure C-4

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
H= 700 M PTS ABOVE

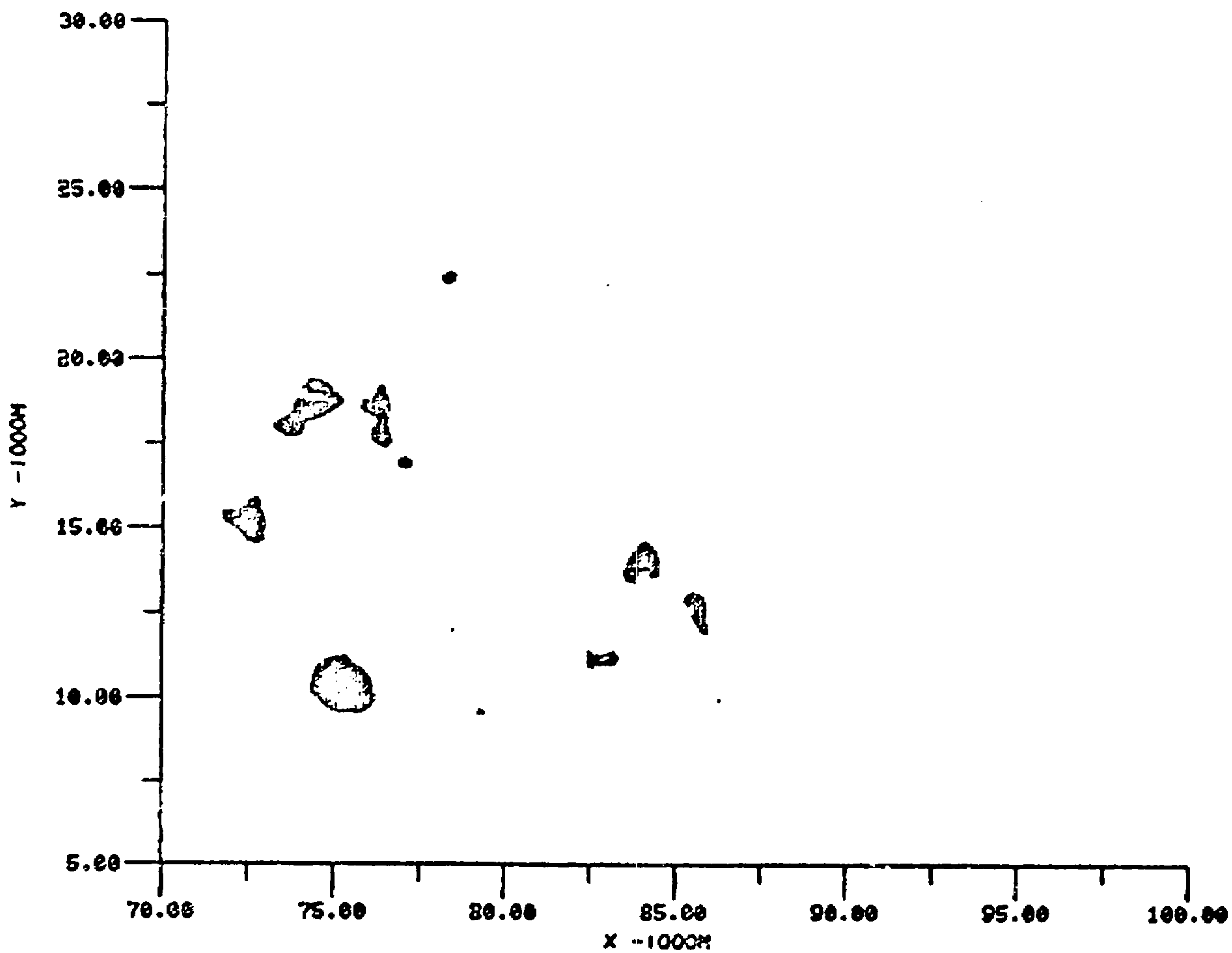


Figure C-5

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
X,Y,H A/C = 95.00 KM, 25.00 KM, 328. M; DH = 61.0 M
LINE OF SIGHT PTS SEEN ARAT = .0599

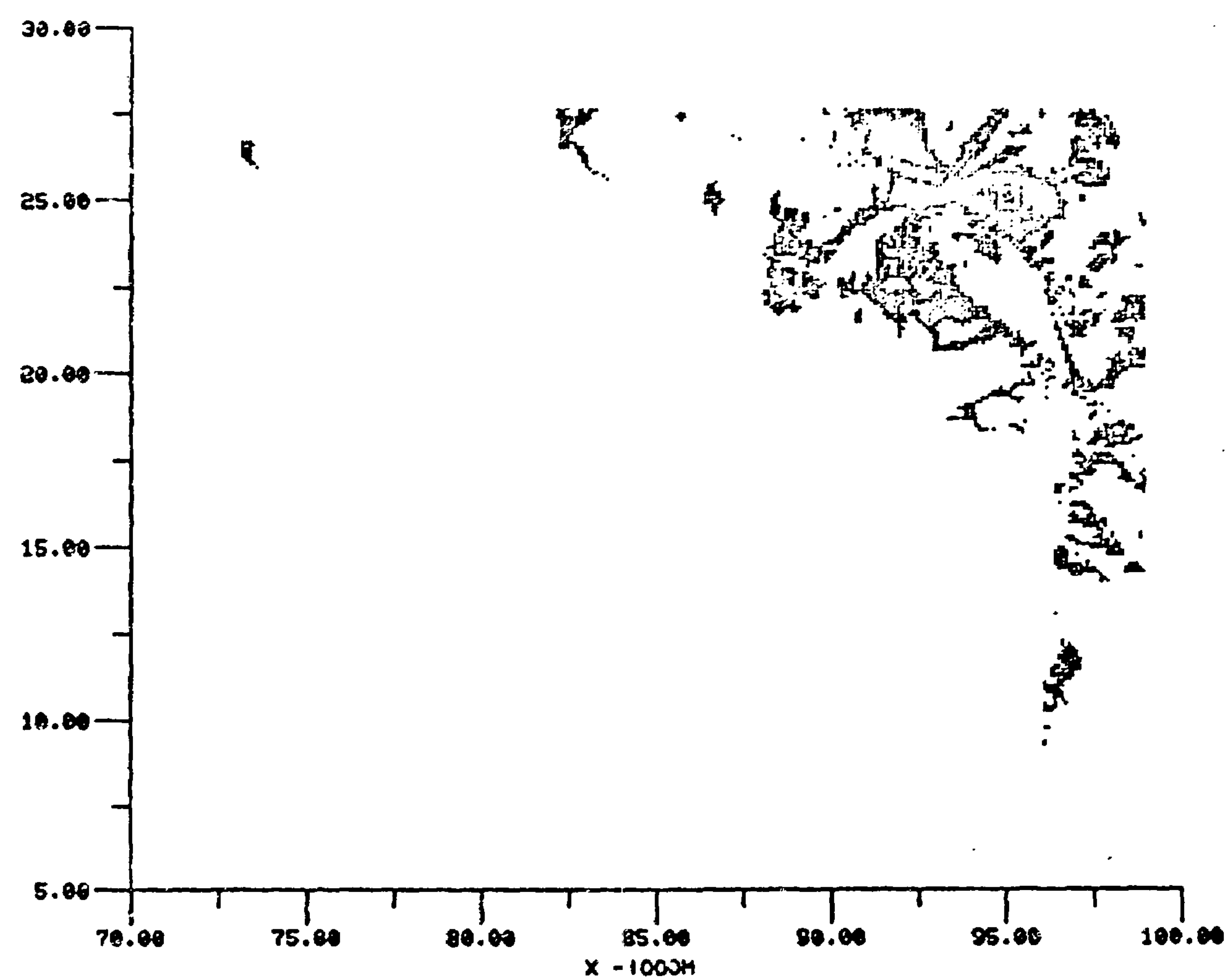


Figure C-6

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
X,Y,H A/C = 95.00 KM, 25.00 KM, 328. M; DH = 61.0 M
LINE OF SIGHT PTS ABOVE ARAT = .0331

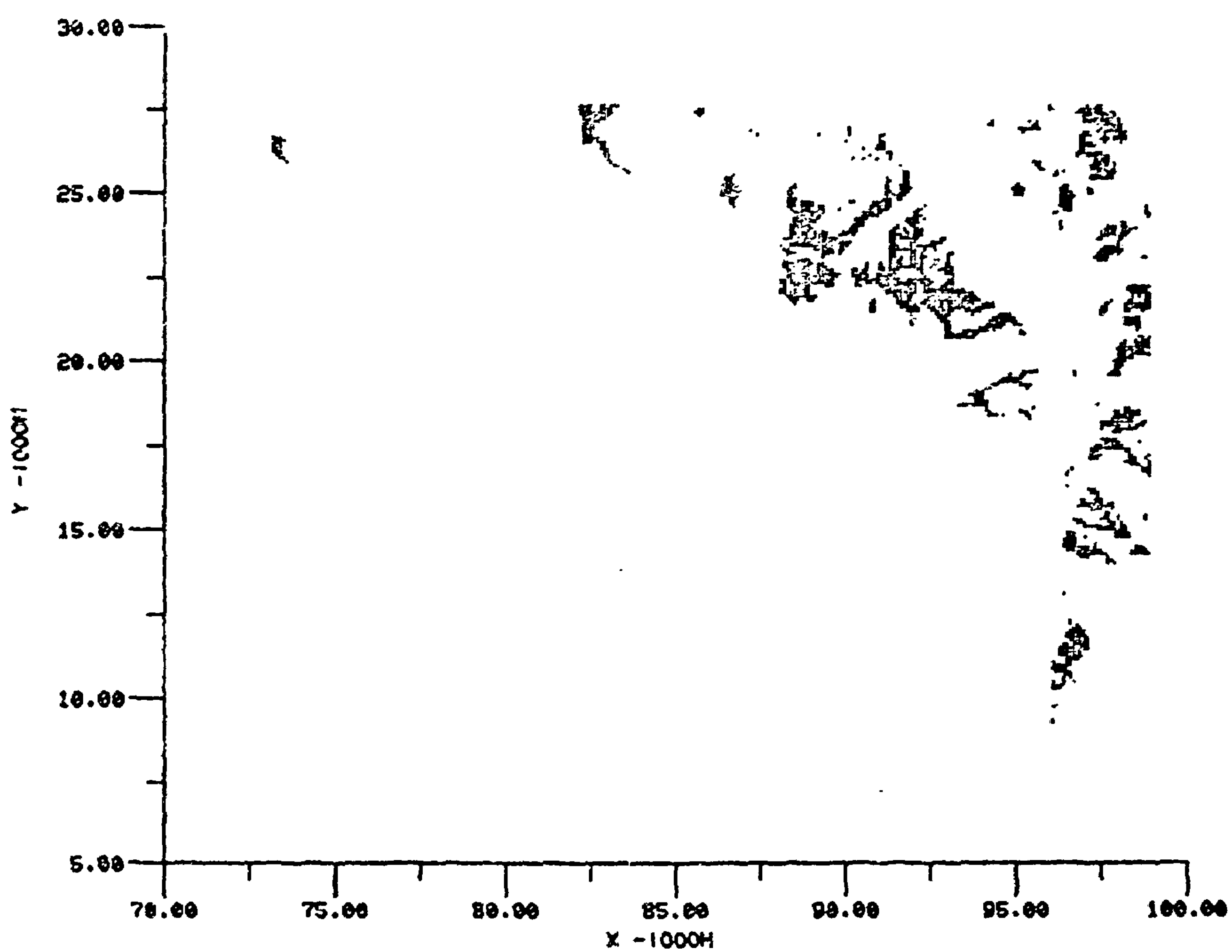


Figure C-7

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
X,Y,H A/C = 95.00 KM, 25.00 KM, 328. M; DH = 61.0 M
LINE OF SIGHT PTS BELOW ARAT = .0263

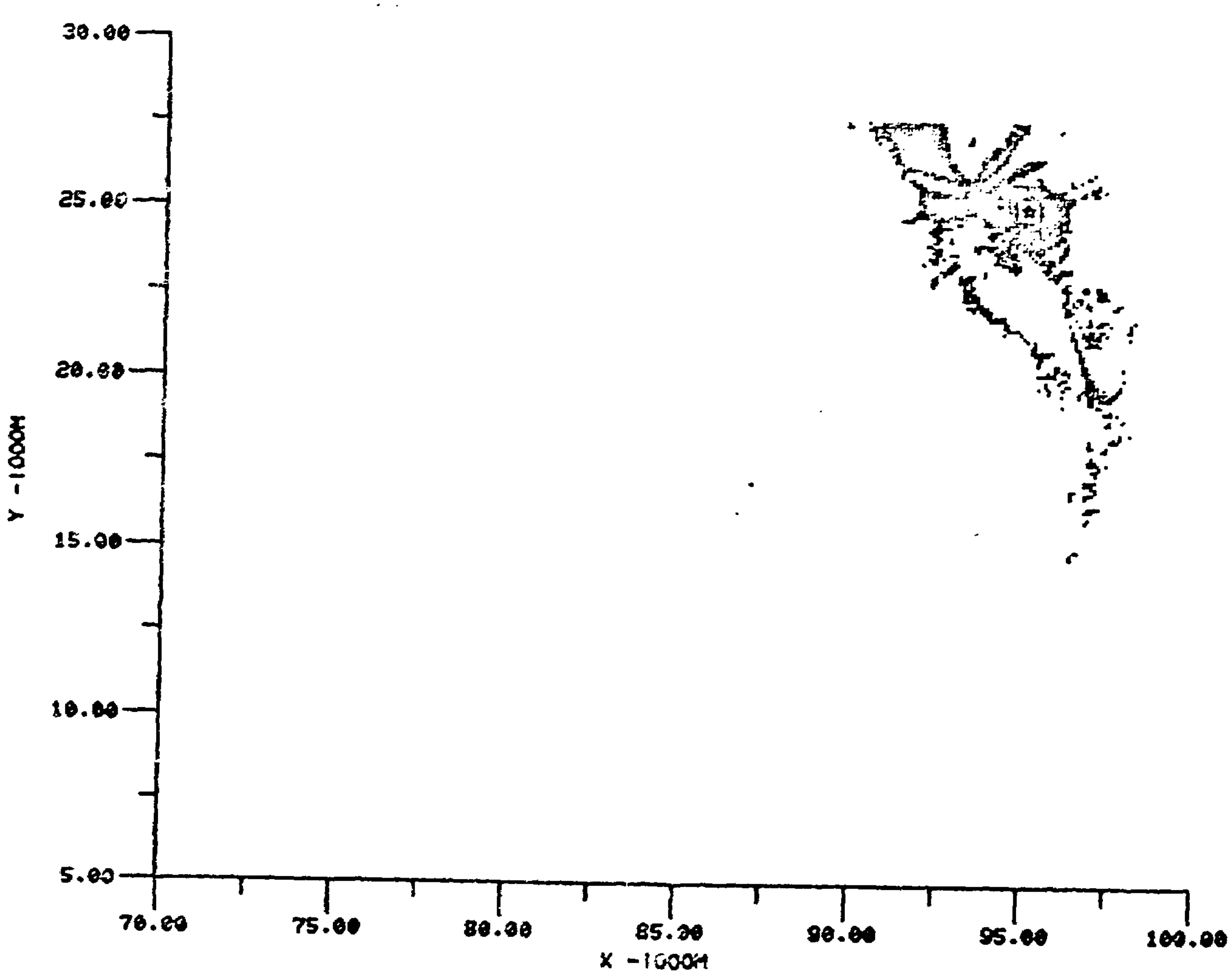


Figure C.8

The user is cautioned to input all option and sub-option values in one contiguous string. There should be only one carriage return per string of data. The reason for this is that data input is not read in by standard FORTRAN IV freefield. There is a specialized input reading subroutine that checks argument number, types, and values. If entries occur on separate lines, only the values on the first line are received. The buffer is not checked for following entries. In short, input all options, and sub-options if required, on one contiguous line. If no sub-options are prompted for at that point, do not provide any.

Option 4 allows the user to generate a flight path for the aircraft. The user may use up to 40 characters to identify or describe the flight path that is being generated. This identification prints out on all subsequent flight path related output. Figure C-9 displays the identification prompt, and Figure C-10 displays the flight path prompt. The first line of flight path input must consist of four values: the X coordinate of the initial point, the Y coordinate of the initial point, the X coordinate of the end point for that leg, and the Y coordinate of the end point for that leg. From that point on, input can be continued by entering succeeding turnpoints in X,Y pairs, or terminated by entering a "P" or an "M" (Figure C-11). The "P" plots out the ground

```
ENTER NAME TO IDENTIFY THIS PATH(MAX OF 40 CHAR)
INPUT:
```

Figure C-9

```
ID OF PATH BEING GENERATED: THESIS TEXT EXAMPLE
ENTER A/C START & END LOCATION (IN METERS) AS XS,YS,XE,YE;
 OR A/C END LOCATION ONLY (IN METERS) AS XE,YE;
   OR P TO PLOT; OR M FOR MASTER MENU
INPUT:
```

Figure C-10

```
ID OF PATH BEING GENERATED: THESIS TEXT EXAMPLE
ENTER A/C START & END LOCATION (IN METERS) AS XS,YS,XE,YE;
 OR A/C END LOCATION ONLY (IN METERS) AS XE,YE;
   OR P TO PLOT; OR M FOR MASTER MENU
INPUT: 72000,8000,95000,26000
INPUT: P
```

Figure C-11

track of the flight path that was just input (Figure C-12). A space and carriage return are required to leave this display. The next display is the actual altitude profile of the flight path in feet above sea level (Figure C-13). Turn points of the flight path (if any) are indicated by stars. If the flight path consisted of more than one leg, another space and carriage return automatically provides the next leg. This process continues until all legs have been displayed, at which point the space and carriage return provides the TERRAIN master menu again. At any point in this display process, the master menu could have been regained by sending an "M" instead of a space.

Option 5 provides five different sub-options. Sub-option 1 allows the user to change any of the 50 radar and aircraft parameters. Input of 5,1 produces Figure C-14, the current vaues of the parameters. Changes are affected by entering the variable number, 1-50, and its new value. Entering a "99" or "?" provides a new print of the parameter list and an opportunity to confirm the change. Input of "100" or "M" regains the master menu. Discussion and definition of the 50 variables in the parameter list appears in Appendix A.

Sub-option 2 allows the user to fly the aircraft over the flight path defined in Option 4. The aircraft's flight parameters and equations of motion combine with the

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=13DE,50D36'N 6AUG80
THESIS TEXT EXAMPLE

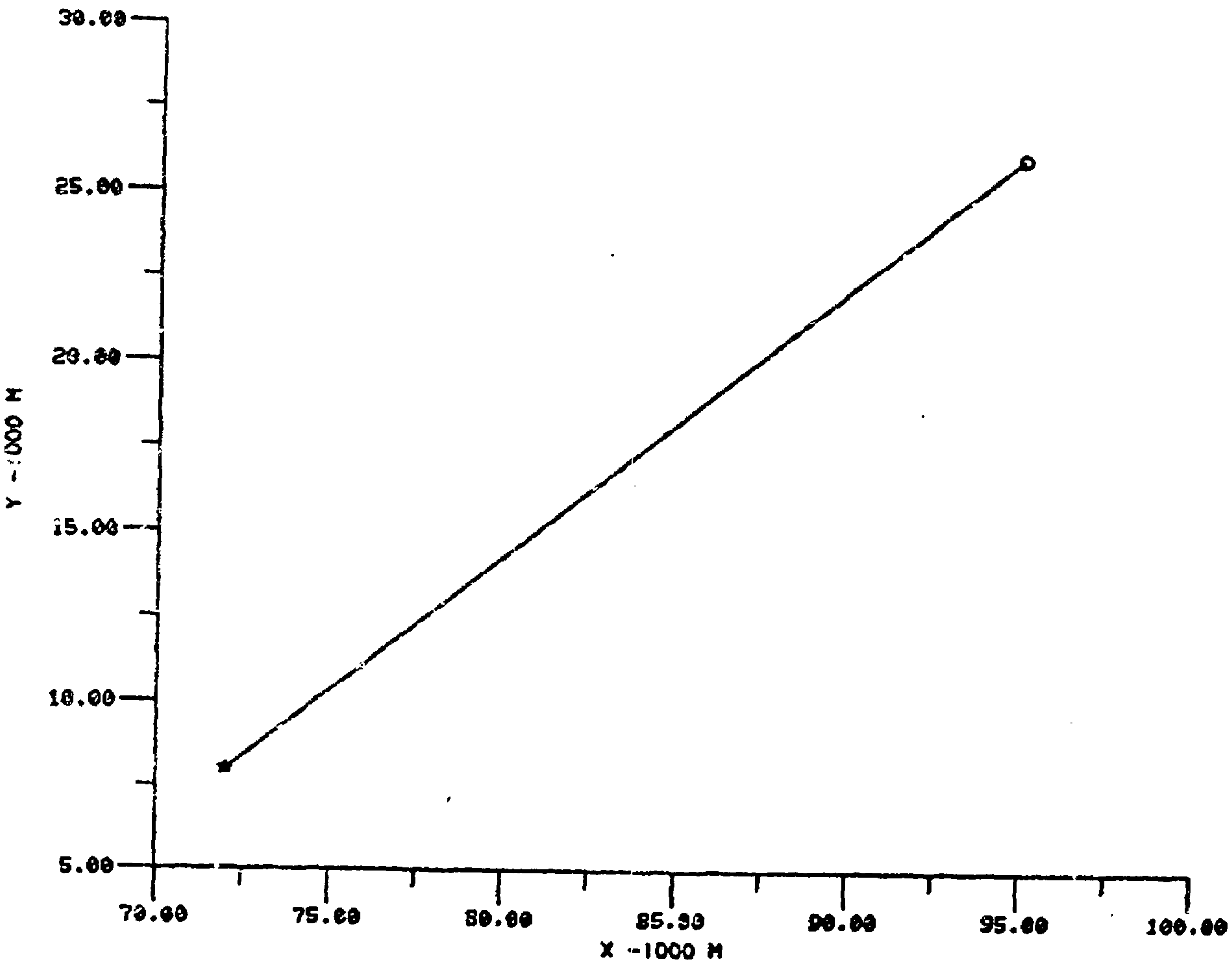


Figure C-12

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG89
THESIS TEXT EXAMPLE SEG = 1
XINIT = 72000.0 M YINIT = 8000.0 M

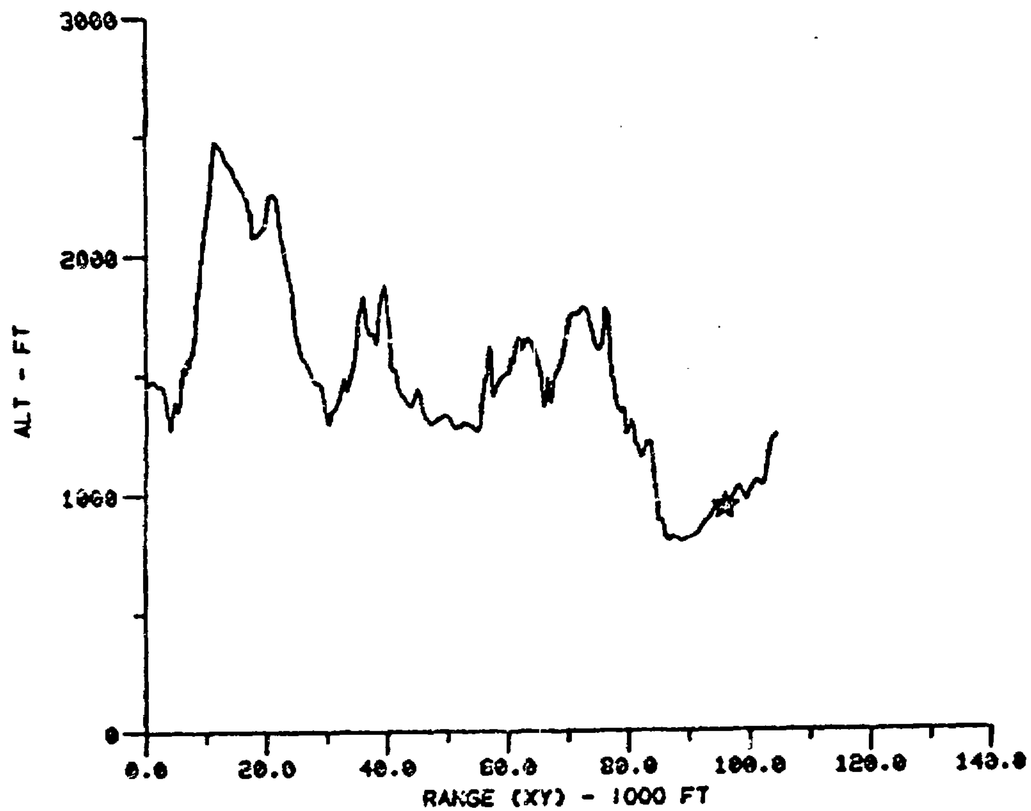


Figure C-13

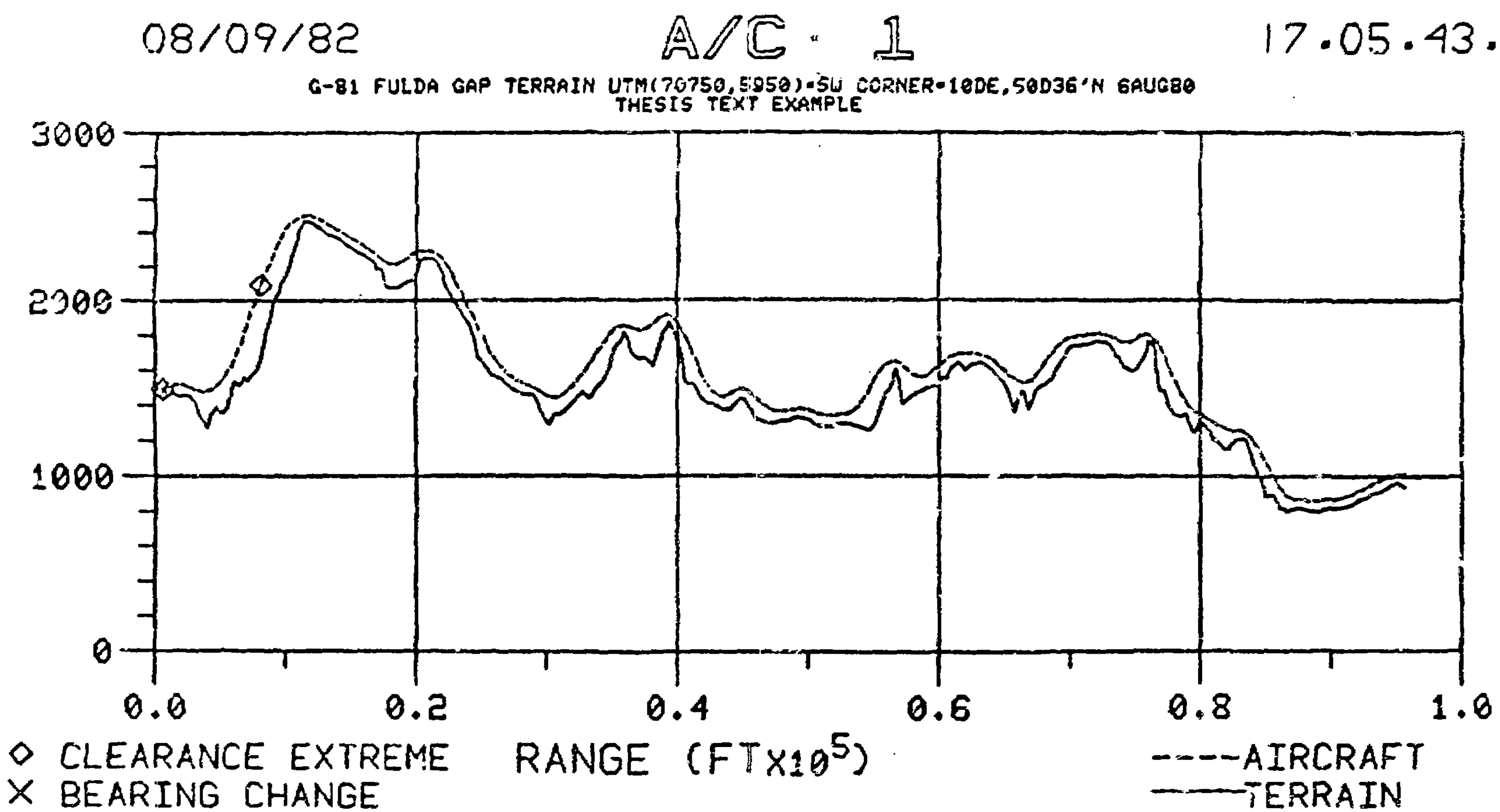
```
MODIFY DAT ARRAY: ENTER LOC,VAL...; OR -LOC,VAL1,VAL2
  1) C1        =  1.300           26) XLAM      =  .5743E-01
  2) C2        =  1.740           27) CKT       =  .4000E-20
  3) C3        =  1.100           28) BWIF      =  .2000E+07
  4) C4        = -.7700           29) RIDE      =  1.000
  5) HO        =  50.00           30) BIAS      =  .2000E-02
  6) RINC      =  9000.           31) ADBPNM    =  .2000E-04
  7) RMIN      =  1000.           32) RDBPNM    =  .6000
  8) TP        =  2.250           33) STEPS     =  1.000
  9) GMCL      =  .3490           34) PRINTMTX  =  1.000
 10) BMAX      =  .4710           35) RLM       = 0.
 11) VAC       =  559.0           36) PAV       =  15.00
 12) STAT      = 0.               37) TAU       =  .3400E-06
 13) RNCL      =  5000.           38) ALPHA     =  .4572E-03
 14) TI        =  .2500           39) TSYS      =  .1000
 15) XKGM      =  .5000E-02       40) RHO       =  .1000
 16) TS        =  .2500           41) D         =  .3281
 17) PT        =  .3000E+05       42) TN        =  .5000
 18) PW        =  .2000E-06       43) PRF       =  .4000E+05
 19) G         =  354.8           44) ACMIN     = -.8000
 20) SIGG      =  .1000           45) ACMAX     =  1.500
 21) SIGR      =  .3060E-05       46) BD        =  .2500E-03
 22) F         =  4.000           47) ALPHAR    =  .3048E-02
 23) BW        =  .1396           48) RHOR      = 0.
 24) RLOS      =  10.00           49) GMDL      = -.5236
 25) GDPT      =  2.000           50) DATS0     = 0.
 99) NEW LIST
100) TERRAIN MENU
INPUT:
```

Figure C-14

required command altitude for terrain following and observation of the underlying and upcoming terrain to produce an altitude profile of the actual flight. Sub-option 2 allows for specification of five different vehicles that are on the data files as well as the option of flying a new vehicle for which the user has made special arrangement to provide data. Specifying "99" for the sub-option at 5,2 flies the aircraft that is currently defined over the current flight path. This implies that this is at least the second run through Option 5.

To fly any of the first five aircraft, the one would input 5,2,1; 5,2,2; etc. If 5,2,6 was input, the user would be queried to define a unique identifier for the new aircraft. If 5,2,99 was input, the appropriate identifier would be accessed, and the same plane that was last flown would be flown with the flight parameters as specified over the new fight path. The master menu reappears at the completion of the flight. NOTE: Option 4 is required prior to use of Option 5,2 and beyond.

Sub-option 3 displays the altitude of the aircraft and the terrain it overflew as a function of range (Figure C-15). The aircraft and radar parameters are provided, as are the summaries on the ride roughness and descriptive statistics (mean, standard deviation, minimum, and maximum) on terrain clearance. The clearance extremes are depicted graphically as are the flight path turn points.



C1	= 1.300	VAC	= 559.8	SIGR	= .3060E-05	ADDPNH	= .2800E-04	D	= .3281
C2	= 1.740	STAT	=0.	F	= 4.000	RDEPNM	= .5000	TM	= .5000
C3	= 1.100	RNCL	= 5000.	BW	= .1335	STEPS	= 1.000	PRF	= .4000E+05
C4	=-.7700	TI	= .2500	RLOS	= 10.00	PRINTMTX	= 1.000	ACMIN	=-.8000
HO	= 50.00	XKCM	= .5000E-02	GDPT	= 2.000	RLM	=0.	ACMAX	= 1.500
RINC	= 9000.	TS	= .2500	XLAM	= .5743E-01	PAV	= 15.00	BD	= .2500E-03
RMIN	= 1000.	PT	= .3000E+05	CKT	= .4000E-20	TAU	= .3400E-06	ALPHAR	= .3048E-02
TP	= 2.250	PW	= .2000E-06	BWIF	= .2000E+07	ALPHA	= .4572E-03	RHOR	=0.
GMCL	= .3490	G	= 351.8	RIDE	= 1.000	TSYS	= .1000	GMDL	=-.5236
BMAX	= .4710	SIGG	= .1000	BIAS	= .2000E-02	RHO	= .1000	DAT50	=0.

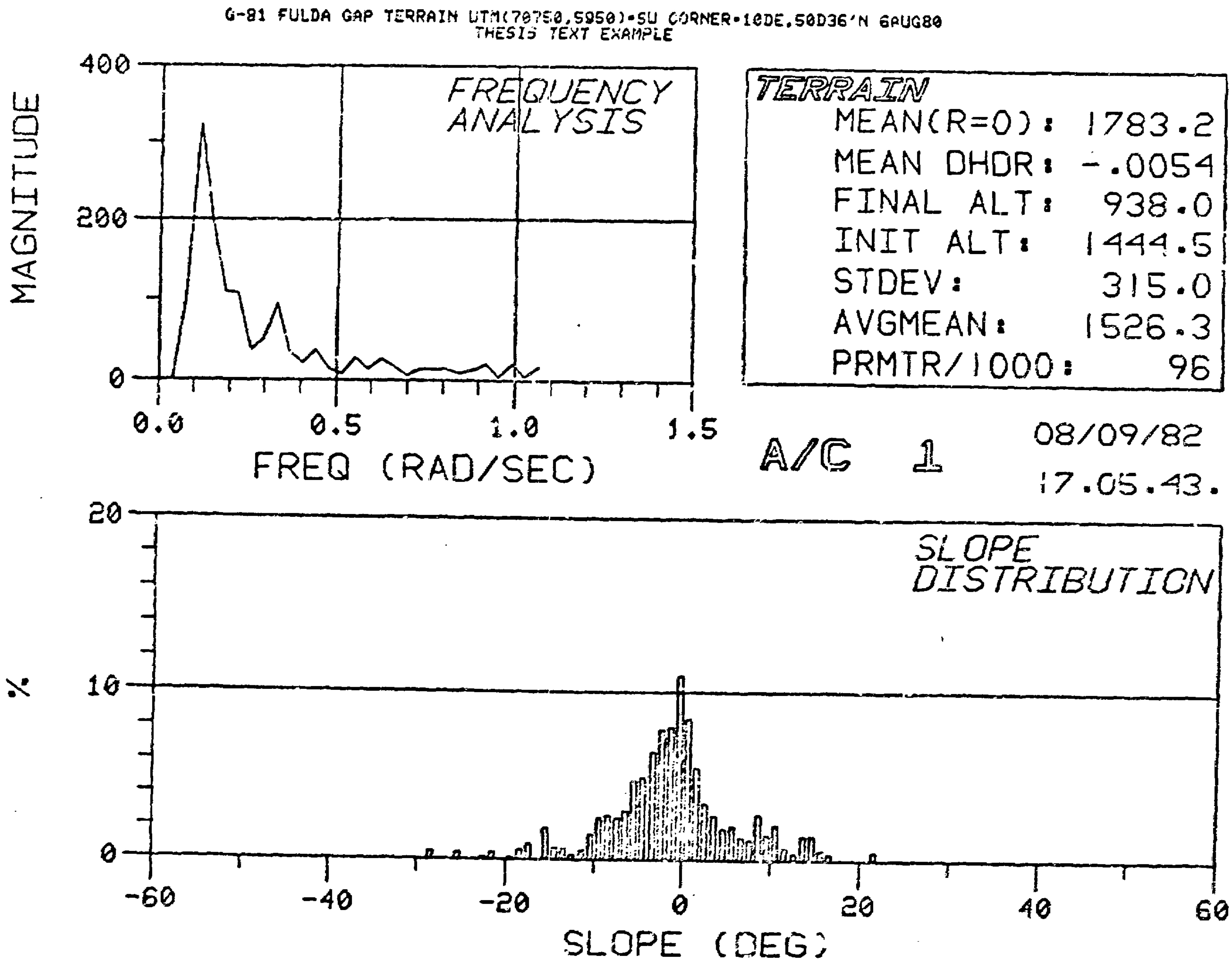
RIDE:HARD, MEAN= 108.3, STDEV= 69.0, MIN/MAX CLEAR= 27.8/ 426.7

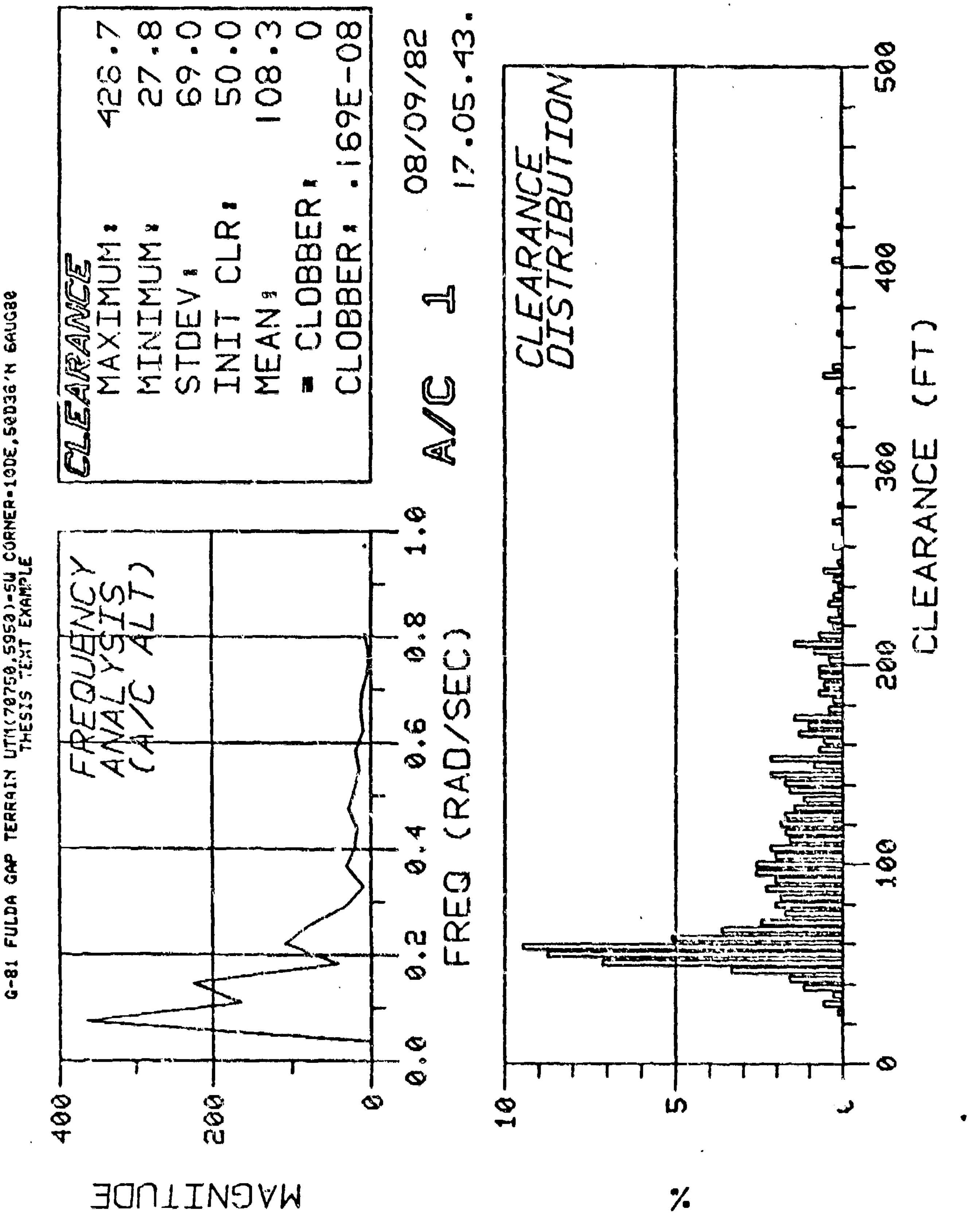
Input of "100" and carriage return regains the master menu. NOTE: Option 5,2 is required prior to the use of Options 5,3 and beyond.

Sub-option 4 provides an analysis of the overflown terrain. The upper left graph of Figure C-16 is a Fourier decomposition of the rate of change of terrain altitude in radians per second. The magnitudes of this graph give some idea of the overall steepness or flatness of the terrain under the aircraft's flight path. The table on the upper right summarizes the key terrain altitude statistics. The graph on the bottom half of the figure depicts the percentage of terrain overflown that had a specific slope. Positive slope is terrain that is increasing in altitude.

Sub-option 5 provides an analysis of the aircraft clearance over the entire flight path. The upper left-hand graph of Figure C-17 plots the Fourier decomposition of the clearance profile. The table on the upper right summarizes the descriptive statistics relating to the clearance. The last value provided there is the probability of clobber (the probability that the aircraft will run itself into the ground with the given command altitude and TF parameters). The graph on the bottom half of the figure presents the percent of the flight path that was flown at the given clearance.

Option 6 provides the user with an extensive set of


G-81 FULDA GAP TERRAIN UTM(70750,5950)-SW CORNER-10DE,50D36'N 6AUG80
THESIS TEXT EXAMPLE
FREQUENCY ANALYSIS
MAGNITUDE
400
200
0
0.0
0.5
1.0
1.5
FREQ (RAD/SEC)
TERRAIN
MEAN(R=0): 1783.2
MEAN DHDR: -.0054
FINAL ALT: 938.0
INIT ALT: 1444.5
STDEV: 315.0
AVGMEAN: 1526.3
PRMTR/1000: 96
A/C 1
08/09/82
17.05.43.
SLOPE DISTRIBUTION
%
20
10
0
-60
-40
-20
0
20
40
60
SLOPE (DEG)


G-81 FULDA GAP TERRAIN UTM(70750,5950)-SW CORNER-10DE,50D36'N 6AUG80
THESIS TEXT EXAMPLE
FREQUENCY ANALYSIS (A/C ALT)
MAGNITUDE
400
200
0
0.0
0.2
0.4
0.6
0.8
1.0
FREQ (RAD/SEC)
CLEARANCE
MAXIMUM: 426.7
MINIMUM: 27.8
STDEV: 69.0
INIT CLR: 50.0
MEAN: 108.3
= CLOBBER: 0
CLOBBER: .169E-08
A/C 1
08/09/82
17.05.43.
CLEARANCE DISTRIBUTION
%
10
5
0
100
200
300
400
500
CLEARANCE (FT)

sub-options and a sub-menu (Figure C-18). This is an instance where the option must be input separately, i.e., 6 with a carriage return, and then the sub-option input follows.

Sub-option 1 provides Figure C-19 and a chance to redefine defensive radar characteristics. The parameters that can be changed are the weapon type index, the minimum and maximum ranges for the radar, the reaction time of the defense, the time the target can be out of LOS before reacquisition is forced, the average velocity of the missile or projectile, the guidance index of the missile (0=unguided, 1=semi-active homing, 2=active homing, 3=IR seeker), the number of weapons per site, the multipath angle (rads), the approaching/receding flag (0=approaching and receding, 1=approaching only, 2=receding only), and the shoot-look-shoot assessment time. The method for affecting changes here is, as before, identification of the location to be changed and the value for that location. The locations are counted from 1 to 144 starting with 1 as the entry for WTYPE in row 1, 2 as RMIN in row 1, 13 as WTYPE in row 2, etc. An "M" entry regains the master menu.

Sub-option 2 provides Figure C-20, the defense location list. The user may change the X,Y location of the defensive unit, the vertical displacement of the center of mass of the defense, and the weapon type.

```
A/C PATH/DEFENSE LOS MENU
(1) MODIFY DEFENSE CHARACTERISTICS (7,2)
(2) MODIFY DEFENSE LOCATIONS (7,2)
(3) CALCULATE A/C LOS TO DEFENSES (6,0)
       DEFAULT IS ACTUAL A/C PATH (TAPE2)
       FOR IDEAL PATH, ENTER: 3,DH IN FT
       DEFAULT IS NO MULTI-PATH ANGLE
       FOR MULTI-PATH, ENTER: -3
(4) DISPLAY DEFENSE LOCATIONS (7,3)
       ENTER: -4 TO ALSO DISPLAY ROADS
(5) DISPLAY A/C & DEFENSES SEEN AT T SEC (7,4)
         ENTER: 5,TIME IN SEC.
(6) DISPLAY LOS TIME HISTORY (7,5)
(7) DISPLAY EFFECTIVE LAUNCH TIME HISTORY (7,6)
     (-1) DEFAULT: USE INPUT DATA
     ( 0) APPROACHING & RECEDING DEFENSES
     ( 1) APPROACHING DEFENSES ONLY
     ( 2) RECEDING DEFENSES ONLY
ENTER M TO GO TO TERRAIN MASTER MENU
INPUT:
```

Figure C-18

```
MODIFY DEFENSE CHARACTERISTICS
LOC    WTYPE     RMIN      RMAX      RTIME    BTIME   AVGVEL   CONTYP   WPNNP   ANGMUL   APPR    SLSAT  UNUSED
  1     1.00   7408.00  59264.00    25.00     2.00   770.40     1.00    6.00      .35    0.00    5.00    0.00
 13     2.00   5556.00  22224.00    13.50     2.00   609.30     1.00    6.00      .35    0.00    5.00    0.00
 25     3.00   7408.00  64820.00    10.00     2.00   770.40     1.00    6.00      .35    0.00    5.00    0.00
 37     4.00   7408.00 277830.00    15.00     2.00   770.40     2.00    6.00      .35    0.00    5.00    0.00
 49     5.00   3704.00  23150.00    17.00     2.00   609.30     2.00    8.00      .15    1.00    5.00    0.00
 61     6.00    926.00   3704.00     1.00     2.00   305.60     3.00    1.00     0.00    0.00    5.00    0.00
 73     7.00   1852.00  14816.00     8.50     2.00   609.30     1.00   12.00      .25    1.00    5.00    0.00
 85     8.00   1852.00   5556.00     5.00     2.00   370.40     3.00    4.00     0.00    2.00    5.00    0.00
 97     9.00     10.00 185200.00    10.00     2.00   770.40     2.00    6.00     0.00    0.00    5.00    0.00
109    10.00     10.00  27780.00    10.00     2.00   609.30     2.00   12.00     0.00    0.00    5.00    0.00
121    21.00     10.00   3000.00     6.00      .25   609.30     0.00   15.00     0.00    0.00    1.00    0.00
133    22.00     10.00   6000.00     6.00      .25   609.30     0.00   15.00     0.00    0.00    1.00    0.00
ENTER LOC,VAL OR ? OR M FOR MENU
INPUT:
```

Figure C-19

MODIFY DEFENSE LOCATION/TYPE

LOC	X M	Y M	DZ M	UTYPE	X M	Y M	DZ M	UTYPE
1	87980.00	16450.00	2.00	21.00	88180.00	18250.00	2.00	21.00
9	89190.00	19200.00	2.00	21.00	91620.00	21050.00	2.00	21.00
17	87910.00	16450.00	2.00	21.00	88020.00	13100.00	2.00	21.00
25	89760.00	11300.00	2.00	21.00	90790.00	10930.00	2.00	21.00
33	97500.00	25850.00	2.00	21.00	92980.00	23740.00	8.00	21.00
41	94760.00	20040.00	2.00	21.00	97600.00	17780.00	2.00	21.00
49	97680.00	16090.00	2.00	21.00	96920.00	14520.00	2.00	21.00
57	93650.00	18600.00	2.00	21.00	90400.00	26850.00	2.00	21.00
65	83020.00	20950.00	2.00	21.00	87250.00	27050.00	2.00	21.00
73	77920.00	25220.00	2.00	21.00	79310.00	19300.00	2.00	21.00
81	87950.00	17180.00	3.00	-8.00	86230.00	18050.00	3.00	-8.00
89	88120.00	19120.00	3.00	-8.00	90580.00	19600.00	3.00	-8.00
97	89810.00	14580.00	3.00	-8.00	83540.00	9700.00	3.00	-8.00
105	87530.00	11890.00	3.00	-8.00	87910.00	14050.00	3.00	-8.00
113	94850.00	21100.00	3.00	-8.00	86550.00	25450.00	3.00	-8.00
121	94500.00	24700.00	3.00	-8.00	93150.00	18540.00	3.00	-8.00
129	96730.00	15500.00	3.00	-2.00	89330.00	12710.00	3.00	-8.00
137	96600.00	13230.00	3.00	-3.00	88700.00	27200.00	3.00	-8.00
145	76100.00	22800.00	3.00	-8.00	93300.00	22510.00	4.00	-5.00
153	89790.00	17160.00	4.00	-5.00	90190.00	11840.00	4.00	-5.00
161	74130.00	21650.00	4.00	-5.00	96230.00	20480.00	2.00	0.00
169	99250.00	19800.00	2.00	0.00	86150.00	19200.00	2.00	0.00
177	90050.00	18600.00	2.00	0.00	95950.00	13000.00	2.00	0.00
185	95050.00	17400.00	2.00	0.00	85750.00	16000.00	2.00	0.00
193	95780.00	15930.00	2.00	0.00	95310.00	15650.00	2.00	0.00
201	95840.00	14190.00	2.00	0.00	93970.00	13320.00	2.00	0.00
209	95930.00	12450.00	2.00	0.00	95300.00	11400.00	2.00	0.00
217	94700.00	10510.00	2.00	0.00	94100.00	9540.00	2.00	0.00
225	93500.00	8570.00	2.00	0.00	92300.00	7600.00	2.00	0.00

ENTER LOC,VAL OR ? OR M FOR MENU
INPUT:

Negative weapon types reflect the capability to engage receding targets. Changes are made as in sub-option 1. Locations read from 1 to 232. An "M" input regains the master menu.

Sub-option 3 allows the user to calculate the LOS between the aircraft and defenses data. Input of 3 calculates LOS based on the flight path generated in 5,2. Input of 3,100 calculates what the LOS data would have been if the aircraft had maintained a perfect, constant, 100 foot terrain clearance. For either of the above cases, entering -3 instead of 3 provides LOS data with consideration of multipath angle. The master menu appears when calculation of LOS data is complete.

Sub-option 4 provides a display of the defense locations (Figure C-21). Different symbols represent different units. The squares are targets, the triangles are WTYPE=5, the vertical crosses are WTYPE=8, and the diagonal crosses are WTYPE=21. A -4 input prints the defense units and overlays roads and political boundaries as well (Figure C-22).

Sub-option 5 provides a plot of the defensive locations that can be seen by the aircraft at a given time into the flight path (Figure C-23). Required input is 5,t where t is less than or equal to mission length in seconds. A t value greater than the actual mission length will cause a fatal error. The defense unit symbols are as

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER-10E,50D36'N 6AUG80
LOCATION OF DEFENSES SCR T=0 DEFENSE SET-UP #1 15AUG80 G81

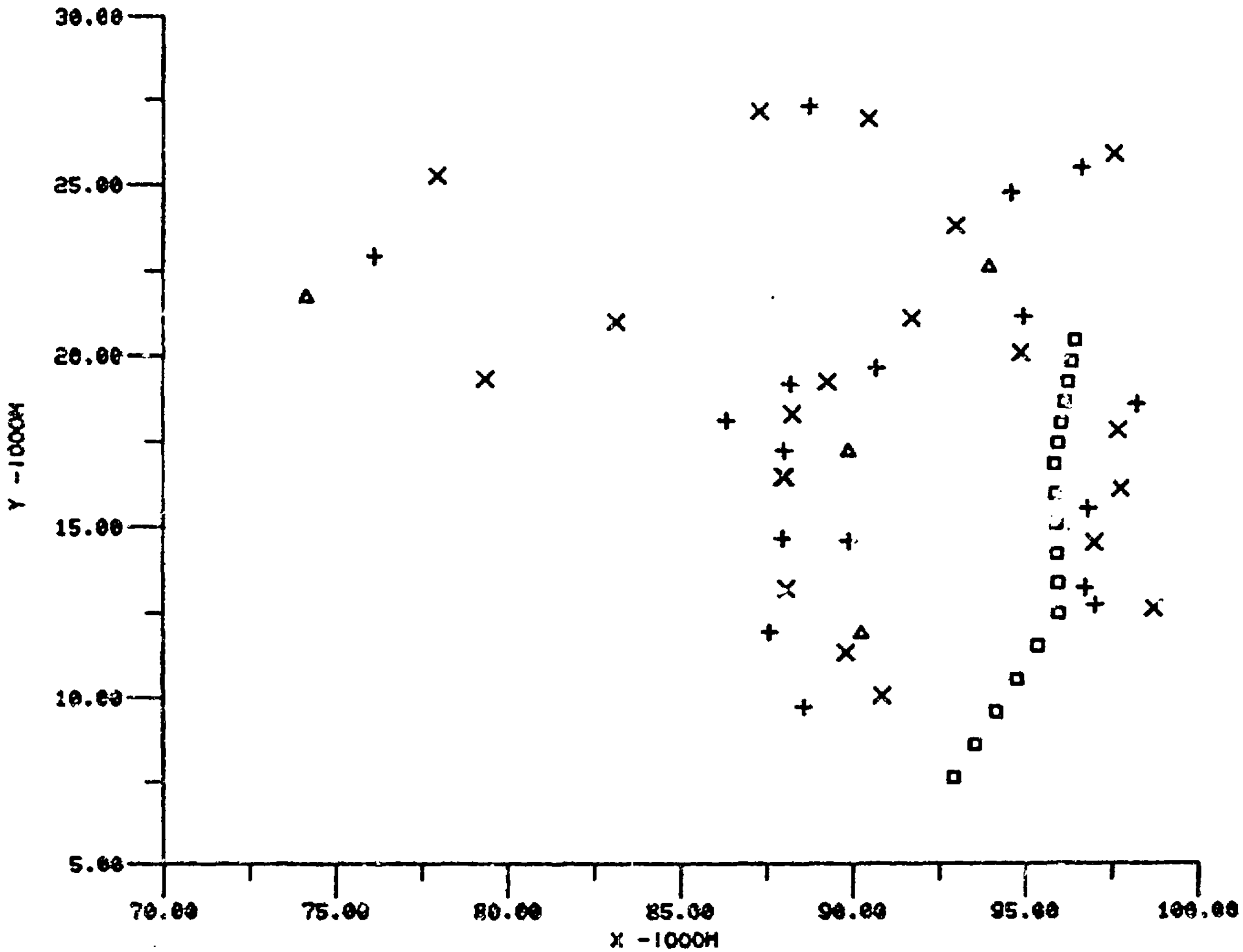


Figure C-21

G-81 FULDA GAP TERRAIN UTM(70730,5950)-SW CORNER-10DE,50D36'N 6AUG80
LOCATION OF DEFENSES SCN 7-0 DEFENSE SET-UP 01 15AUG80 G81

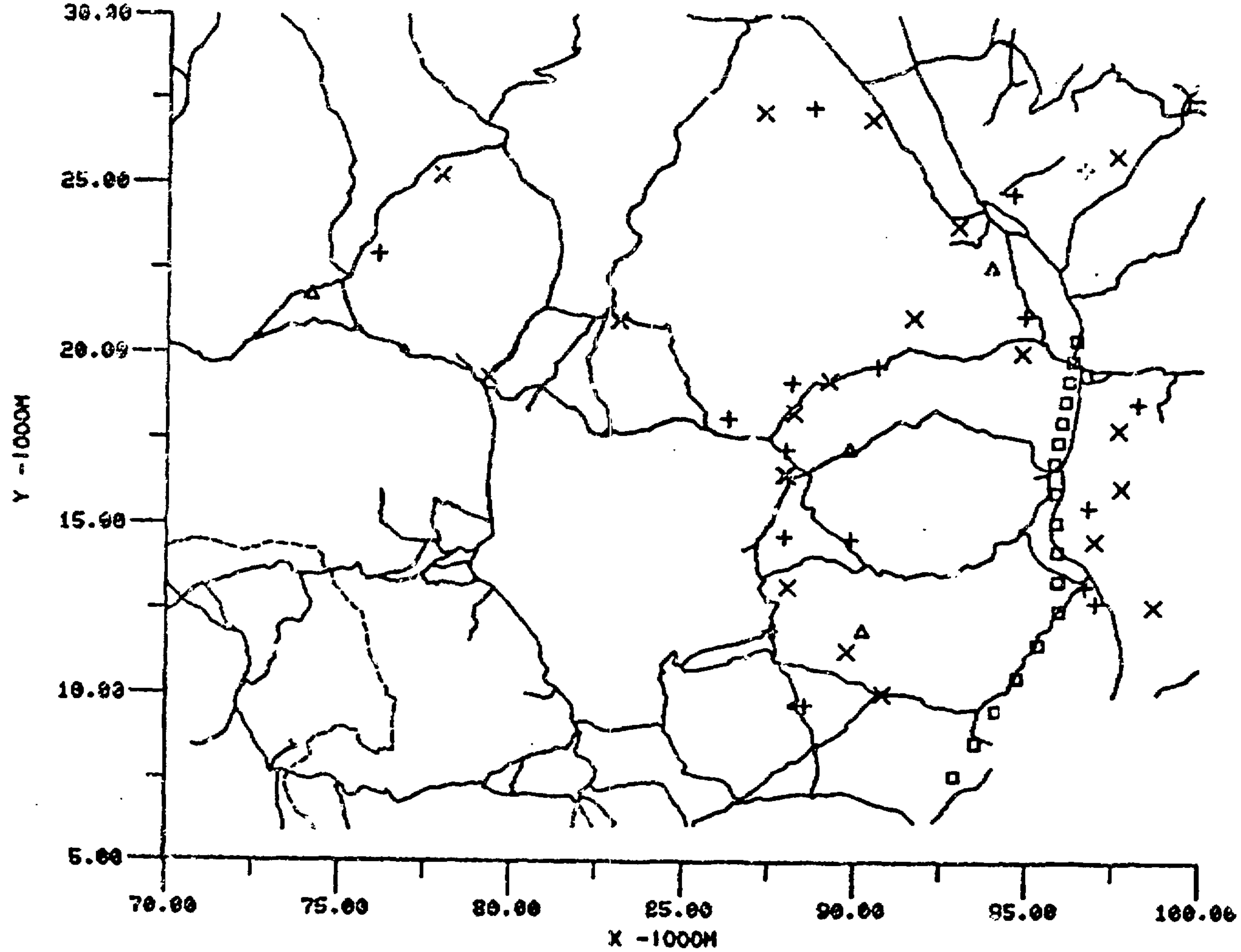


Figure C-22

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
THESIS EXAMPLE TEST SCR T=0 DEFENSE SET-UP #1 15AUG80 GB1
X,Y,H A/C = 88.05 KM, 20.56 KM, 546. M; DH = 125.1 M
DEFENSES SEEN = 8

A/C #1 HARD RIDE

03/09/82 17.31.16.
NO MULTI-PATH ANGLE

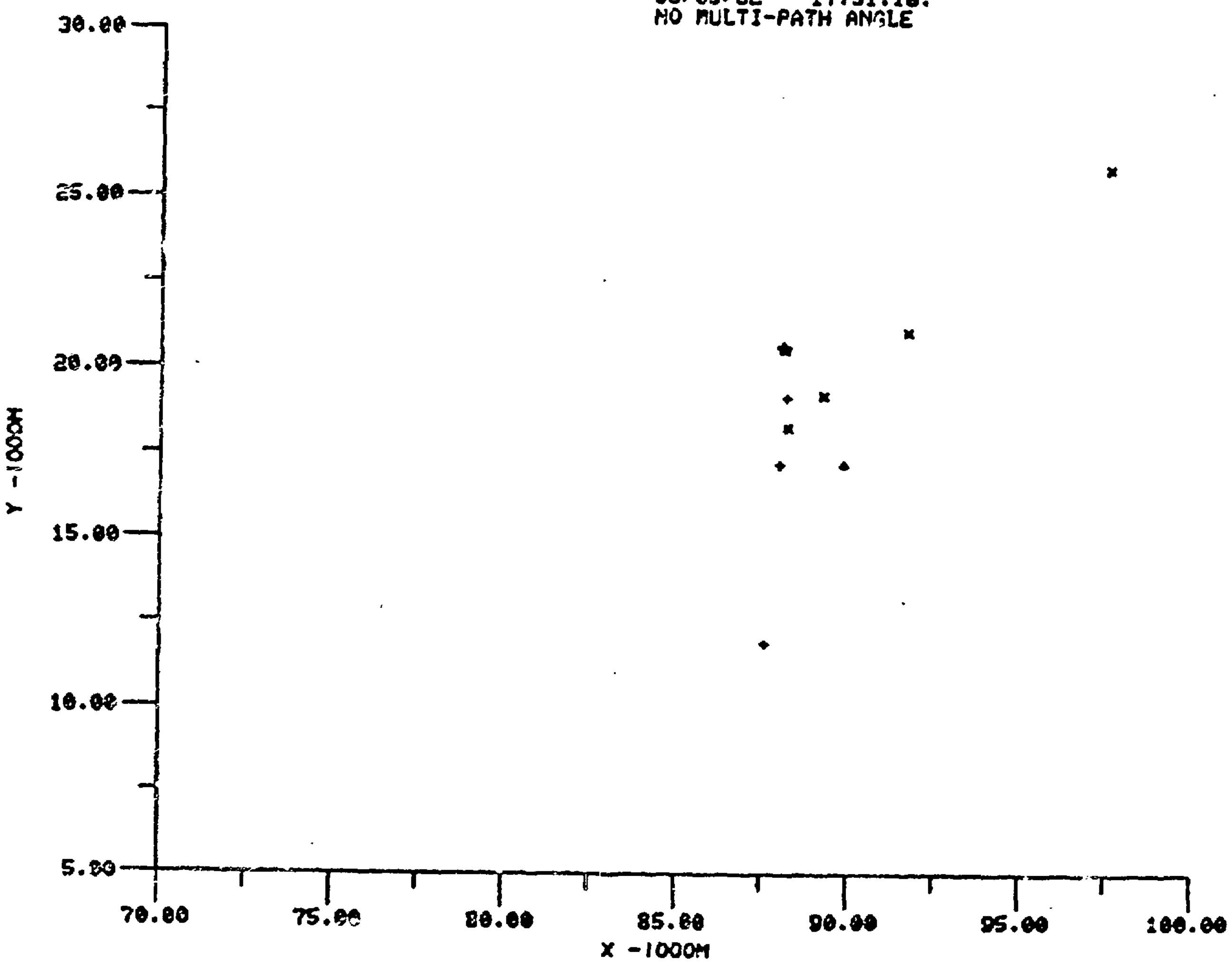


Figure C-23

before. The aircraft is represented by a star. A blank and carriage return regains the master menu.

Sub-option 6 plots the intervals of time during the flight that the aircraft was unmasked to each of the defense units (Figure C-24). The vertical axis lists the threat index, and the horizontal axis tracks the unmask time in seconds. The threat symbols are as before. The total exposure time is listed in the header. A blank and carriage return regains the master menu.

Sub-option 7 plots the effective launch time history. The user may select at this point among several other sub-options. 7,-1 accesses the data produced by a prior run (invocation parameter TAPE4). The remaining options deal with the data produced by the current run. 7,0 examines all sites, those that consider approaching as well as receding aircraft. 7,1 examines the units that consider only approaching aircraft. 7,2 examines the units that play only receding aircraft. Regardless of the specification of the second sub-option, the user sees the plots type menu, Figure C-25.

```
EFFECTIVE LAUNCH TIME HAS BEEN CALCULATED
ENTER P FOR PLOT WITH LOS
ENTER N FOR PLOT WITHOUT LOS
ENTER M FOR LOS/LAUNCH MENU
INPUT:
```

Figure C-25

G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
THESIS EXAMPLE TEST
SCR T=0 DEFENSE SET-UP #1 15AUG80 G81

A/C #1 HARD RIDE

08/09/82 17.30.30.
TIME A/C EXPOSED = 414.0 SEC.
NO MULTI-PATH ANGLE

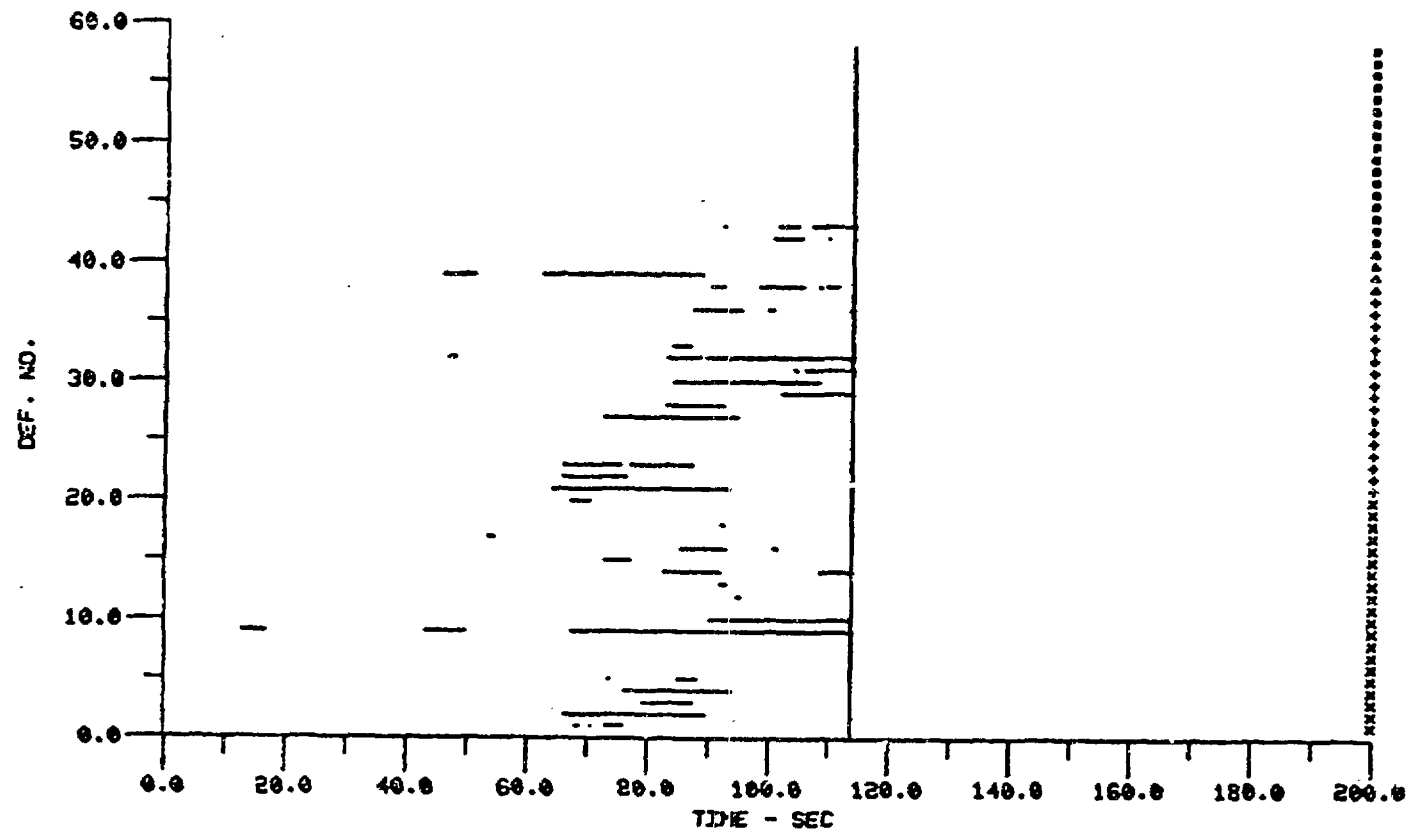


Figure C-24

Choosing "P" plots the exposure time intervals as in sub-option 6, the number of effective launches, and the probability of kill (Figure C-26). Symbols are plotted to identify key points along the flight path. A square designates where a launch occurred, a diamond designates where an intercept should have occurred, a circle designates a miss (because some missile parameter limit was exceeded), and a star designates where in the sequence of fire of a AAA gun a tube overheated and had to slow its rate of fire. Choosing "N" provides the same plot as the "P" option but without the exposure time intervals from sub-option 6 plotted (Figure C-27). A blank with carriage return regains the plot type menu.

Option 7 allows the user to specify a defensive unit by X,Y coordinates and an aircraft's command altitude in feet, and is provided with a plot of the area in which the defensive unit would be able to see the aircraft. Input of 7,87950,17180,200 provides the plot shown in Figure C-28. A blank and a carriage return regains the master menu.

Option 8 allows the user to specify an aircraft altitude, and then plots the boundaries of the lethal envelopes of all the threats in the data base at that altitude (Figure C-29).

G-81 FULDA GAP TERRAIN UTM(70750,5950)-SW CORNER-10DE,50D36'N 6AUG80
THESIS EXAMPLE TEST SCR T-0 DEFENSE SET-UP #1 15AUG80 G81

A/C #1 HARD RIDE

08/09/82 17.22.59.
EFFECTIVE EXP TIME 49.8 SEC.
) MULTI-PATH ANGLE
NO. EFFECTIVE LAUNCHES = 31.
PROBABILITY OF KILL = .4765

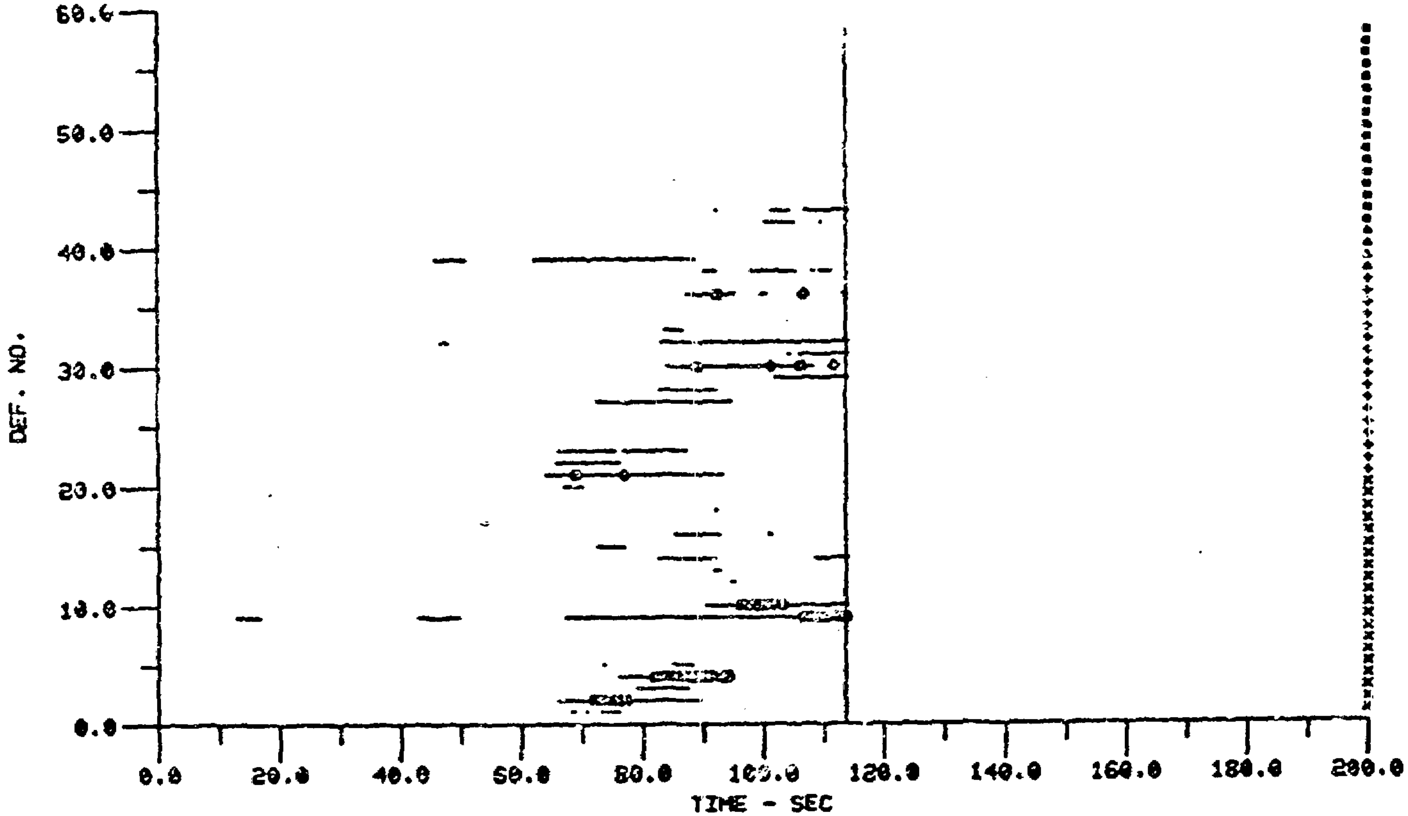


Figure C-26

G-81 FULDA GAP TERRAIN UTM(70750,5950)-SW CORNER-10DE.50D36'N SAUG80
THESIS EXAMPLE TEST SCR T-0 DEFENSE SET-UP #1 15AUG80 G81

A/C #1 HARD RIDE

03/09/83 17.34.02.
EFFECTIVE EXP TIME 49.8 SEC.
NO MULTI-PATH ANGLE
NO. EFFECTIVE LAUNCHES = 31.
PROBABILITY OF KILL = .4765

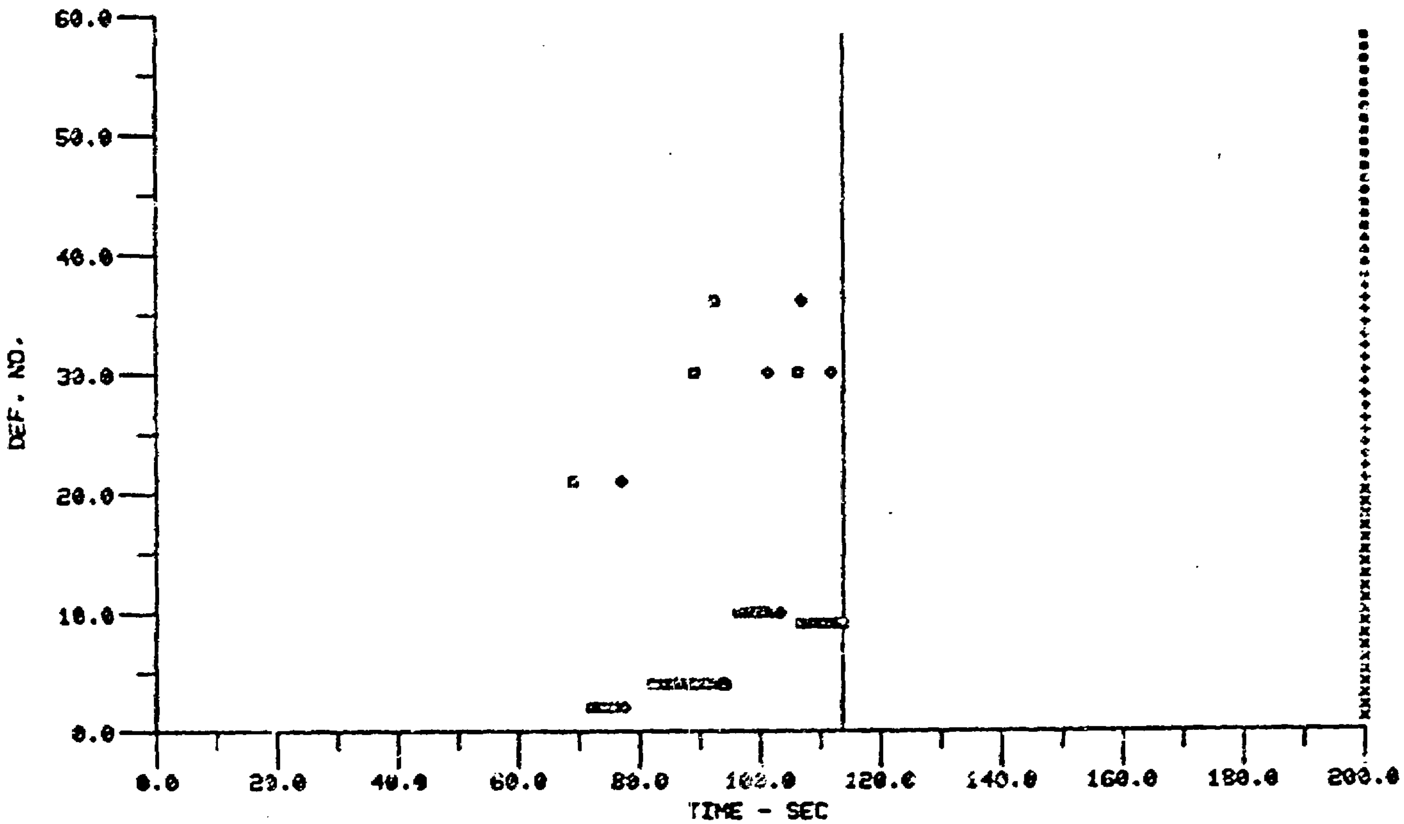
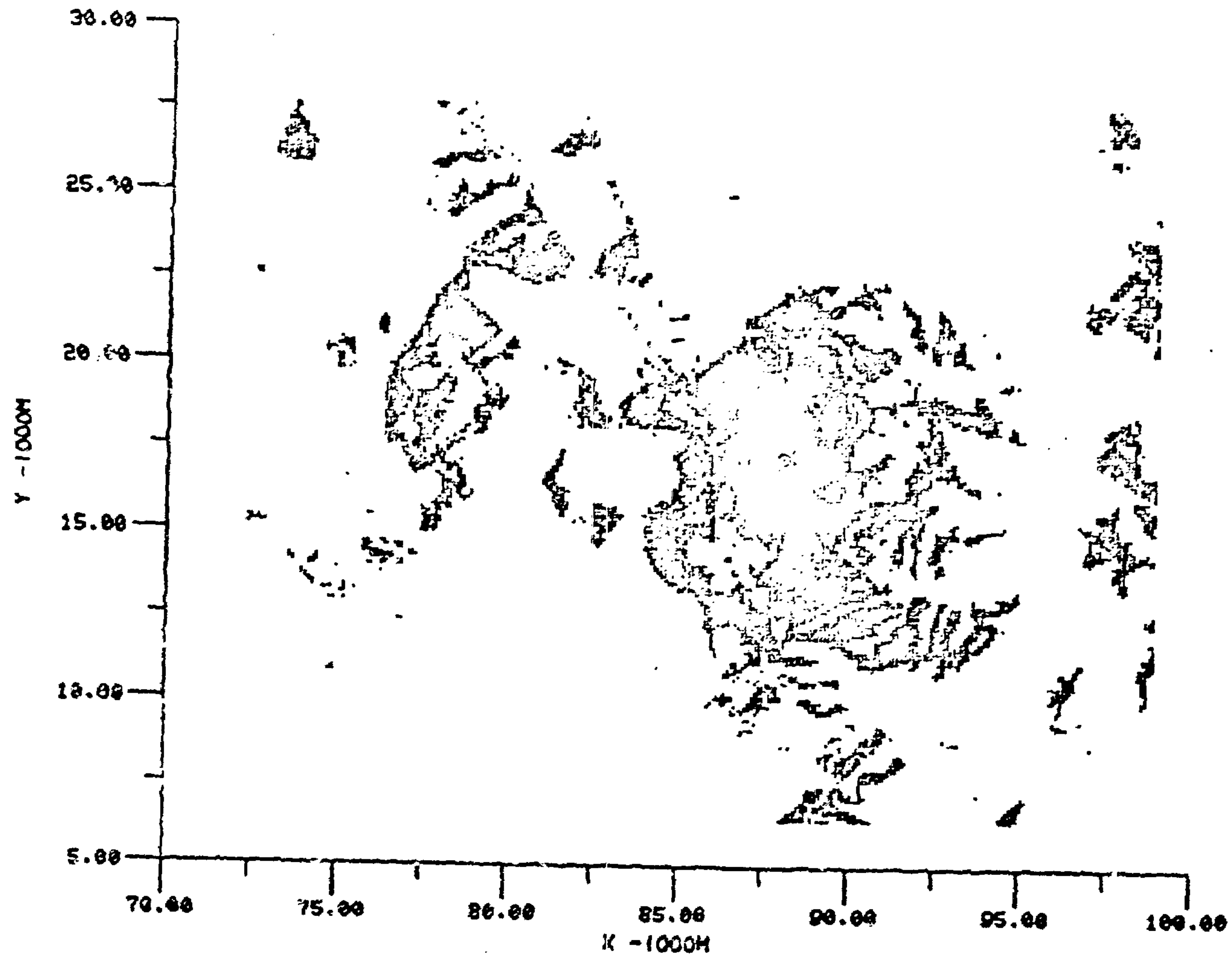


Figure C-27

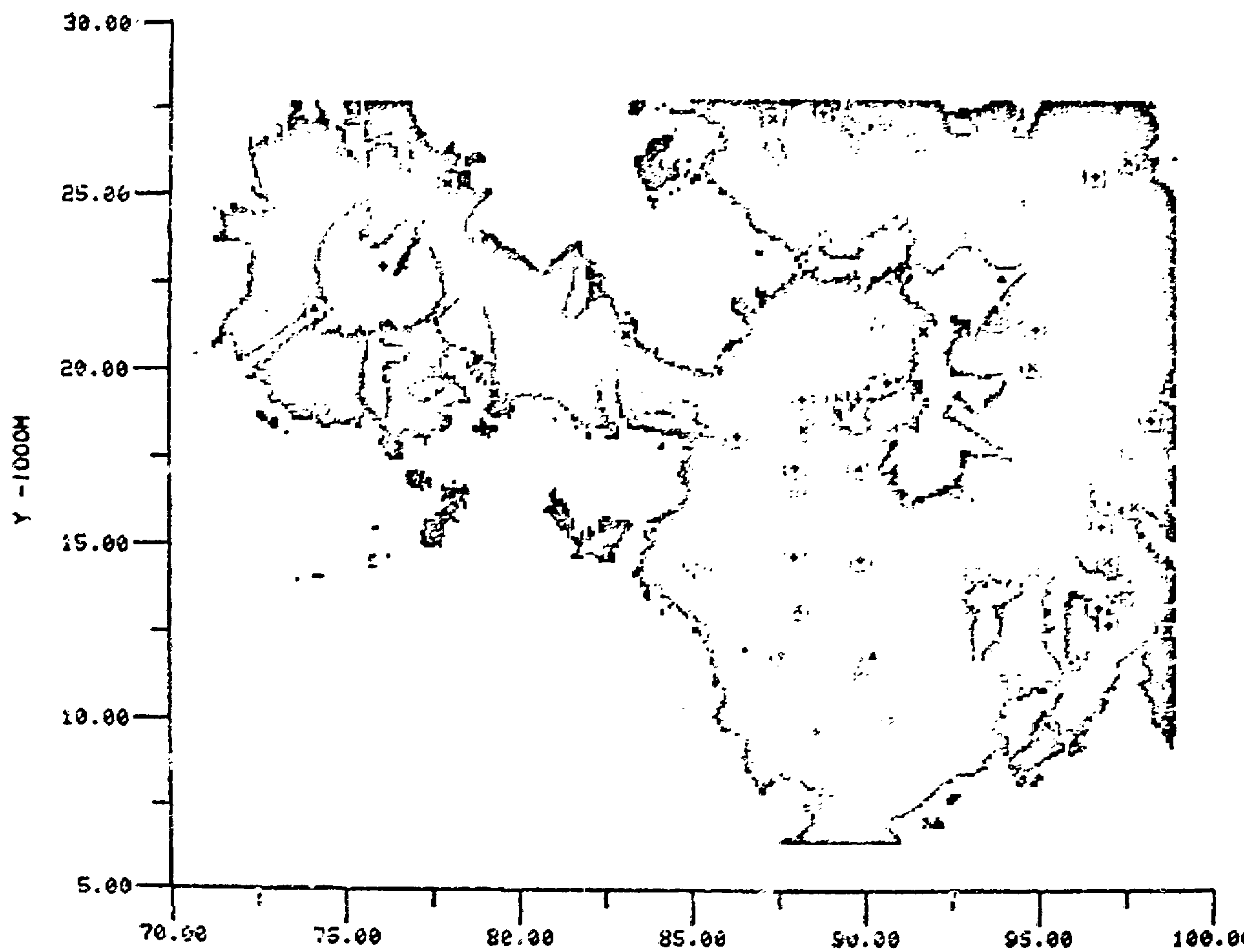
G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
X,Y,H DEF = 37.95 KM, 17.18 KM, 569. M; A/C DH = 0.0 M
LINE OF SIGHT TO A/C
ARAT = .1584



G-81 FULDA GAP TERRAIN UTM(70750,5950)=SW CORNER=10DE,50D36'N 6AUG80
SCR T=0 DEFENSE SET-UP #1 15AUG80 G81
LINE OF SIGHT TO A/C
INCLUDES MULTI-PATH & RANGE

ARAT = .4978

A/C DELTA H = 61.0 M



Appendix D

Description of Variables in Parameter Table

C1, C2, C3, and C4 represent the flight path angle gains. The terrain following flight path algorithm uses those values in some linear combination to generate flight path command guidance.

HO is the command altitude in feet of clearance above the underlying terrain.

RMIN is the minimum distance in front of the aircraft that the radar can see.

RINC is the increment of distance beyond RMIN which the radar can see.

TP is the length of time in seconds forward from the current time that the flight path will be extended in terms of the predictions made by the ADU prior to firing (Time of Prediction).

GMCL is the climb limit on the aircraft flight path in radians (Gamma Climb Limit).

BMAX is the maximum radar downlook angle measured in radians, positive downward.

VAC is the velocity of the aircraft in feet per second.

STAT is the flag which determines whether weather effcts are played, 0=no, 1=yes.

RNCL is the depth in feet of the weather cell under

consideration.

TI is the time increment in seconds between updates of state variables.

XKGM is the gain in forward loop flight path angle. The difference between sensed and command flight path angle is multiplied by XKGM to produce the required g command for the aircraft (X Gamma).

TS is the time increment in seconds for radar range equation updates (Time between Samples).

PT is the power of the transmitter in watts.

PW is the pulse width in seconds.

G is the antenna gain in dB.

SIGG is the one standard deviation (RMS) value of the flight path angular deflection in radians.

SIGR is the one standard deviation value of the flight path range error.

F is the pattern propagation factor between antennae.

BW is the bandwidth in Hz.

RLOS is the power loss factor due to range.

GDPT is the number of usable radar return points.

XLAM is the radar wavelength in meters.

CKT is a combination of constants, including Stefan's and Boltzman's.

BWIF is the bandwidth in Hz of the intermediate frequency of the radar receiver.

RIDE is the flag that specifies how many vertical g's

the aircraft will sustain in its terrain following flight.

BIAS is the radar angular bias error in radians.

ADBPNM is the one way attenuation in clear atmosphere in dB per NM.

RDBPNM is the one way attentuation in rainy atmosphere in dB per NM.

STEPS is the number of processing steps between radar scans.

PRINTMTX is the flag that specifies whether or not the tables containing the values of flight parameters ect. should be dumped to the output file.

RLM is a flag which specifies whether or not lasers are to be used in determining the terrain following flight path.

PAV is the average power of the laser.

TAU is the pulse width of the beam in seconds.

ALPHA is the clear atmosphere attenuation per foot.

TSYS is the transmitivity of the system in dB.

RHO is the target reflectivity in clear weather in dB.

D is the effective aperture of the optical system in feet.

TN is the quantum efficiency of the lasing medium and process.

PRF is the pulse repetition frequency in Hz.

ACMIN is the maximum negative g level that the aircraft will be allowed to sustain.

ACMAX is the maximum positive g level that the aircraft will be allowed to sustain.

BD is the beamwidth of the laser in radians.

ALPHAR is the rainy atmosphere attenuation per foot.

RHOR is the rainy atmosphere reflectivity per foot.

GMDL is the aircraft flight path dive limit (Gamma Dive Limit).

DAT50 is not used.

Appendix E

Sensitivity Runs Test Design

RUN #	DESCRIPTION
1	Test small footprint with close minimum look.
2	Test large footprint with larger minimum look.
3	Test very large footprint with close minimum look.
4	Test very large footprint with close minimum look, no ECM.
5	Decrease RCS by factor of 10.
6	Decrease RCS by factor of 10, no ECM.
7	Decrease RCS by factor of 100.
8	Decrease RCS by factor of 100, no ECM.
9	Change AAA burst size from 20 to 8.
10	Change AAA burst size from 20 to 12.
11	Change reaction time required for radar missiles from 17 to 20 seconds.
12	Change reaction time required for radar missiles from 17 to 13 seconds.
13	Change reaction time required for IR missiles from 5 to 8 seconds.
14	Change reaction time required for IR missiles from 5 to 2 seconds.
15	Change reaction time required for AAA from 6 to 8 seconds.

16 Change reaction time required for AAA from 6 to 4 seconds.

17 Change loss of LOS time required for break lock on radar sites from 2 to 3 seconds.

18 Change loss of LOS time required for break lock on radar sites from 2 seconds to 1 second.

19 Change loss of LOS time required for break lock on IR sites from 2 to 3 seconds.

20 Change loss of LOS time required for break lock on IR sites from 2 seconds to 1 second.

21 Change loss of LOS time required for break lock on AAA sites from .25 to .50 seconds.

22 Change munitions limit for radar sites from 8 to 6.

23 Change munitions limit for radar sites from 8 to 10.

24 Change munitions limit for IR sites from 4 to 6.

25 Change munitions limit for IR sites from 4 to 2.

26 Change munitions limit for AAA sites from 12 to 15.

27 Change munitions limit for AAA sites from 12 to 9.

28 Change the shoot-look-shoot assess time for radar sites from 5 to 7 seconds.

29 Change the shoot-look-shoot assess time for radar sites from 5 to 3 seconds.

30 Change the shoot-look-shoot assess time for IR sites from 5 to 7 seconds.

31 Change the shoot-look-shoot assess time for 1R sites from 5 to 3 seconds.

32 Change the shoot-look-shoot assess time for the AAA sites from 1 to 2 seconds.

33 Change the shoot-look-shoot assess time for the AAA sites from 1 to .5.

34 Change all radar and IR sites from shoot-look-shoot to continuous fire and leave the time between fires unchanged.

35 Change the mode of fire of radar sites from shoot-look-shoot to continuous and the time between fires from 5 to 7 seconds.

36 Change the mode of fire of radar sites from shoot-look-shoot to continuous and the time between fires from 5 to 3 seconds

37 Change the mode of fire of IR sites from shoot-look-shoot to continuous and the time between fires from 5 to 7.

38 Change the mode of fire of IR sites from shoot-look-shoot to continuous and the time between fires from 5 to 3.

Appendix F

PK Results of Sensitivity Runs

RUN		VELOCITY=559/844/1342
1	HO=200	.99/.93/.10
	HO=1000	.61/.68/.65
	HO=2000	.54/.59/.62
2		.97/.98/.11
		.57/.73/.66
		.54/.57/.63
3		.99/.93/.10
		.61/.68/.65
		.54/.59/.62
4		.99/.93/.10
		.99/.98/.79
		.99/.97/.77
5		.99/.93/.10
		.61/.68/.65
		.53/.59/.62
6		.99/.93/.10
		.61/.68/.65
		.72/.59/.62
7		.99/.93/.10
		.61/.68/.65
		.53/.59/.62
8		.99/.93/.10
		.61/.68/.65
		.53/.59/.62
9		.95/.67/.04
		.33/.38/.34
		.29/.31/.32
10		.99/.81/.06
		.44/.50/.46
		.39/.42/.44
11		.99/.93/.10
		.61/.68/.65
		.55/.59/.62

12	.99/.93/.10 .61/.68/.65 .53/.61/.62
13	.99/.93/.10 .61/.67/.65 .54/.57/.62
14	.99/.93/.10 .61/.67/.65 .54/.57/.62
15	.99/.25/.00 .61/.85/.60 .53/.58/.61
16	.99/.95/.50 .62/.62/.69 .58/.63/.62
17	.99/.93/.10 .61/.68/.65 .58/.63/.62
18	.99/.93/.10 .61/.68/.65 .54/.59/.62
19	.99/.93/.10 .61/.68/.65 .54/.59/.62
20	.99/.93/.10 .61/.68/.65 .54/.59/.62
21	.99/.93/.10 .61/.68/.65 .54/.59/.62
22	.99/.93/.10 .61/.68/.65 .54/.59/.62
23	.99/.93/.10 .61/.68/.65 .54/.59/.62

24	.99/.93/.10
	.61/.68/.65
	.54/.59/.62
25	.99/.93/.10
	.61/.68/.65
	.54/.59/.62
26	.99/.93/.10
	.95/.91/.65
	.90/.79/.62
27	.99/.93/.10
	.54/.48/.53
	.41/.40/.39
28	.99/.93/.10
	.61/.68/.65
	.54/.59/.62
29	.99/.93/.10
	.61/.68/.65
	.54/.59/.62
30	.99/.93/.10
	.61/.68/.65
	.54/.59/.62
31	.99/.93/.10
	.61/.68/.65
	.54/.59/.62
32	.85/.49/.08
	.79/.65/.36
	.74/.55/.34
33	1.0/.99/.18
	.99/.98/.87
	.96/.90/.80
34	.99/.93/.10
	.62/.68/.65
	.58/.59/.62
35	.99/.93/.10
	.62/.68/.65
	.56/.59/.62
36	.99/.93/.10
	.62/.68/.65
	.58/.59/.62

37	.99/.93/.10 .61/.68/.65 .57/.59/.62
38	.99/.93/.10 .62/.68/.65 .58/.59/.62

Vita

Mark D. Reid was born 13 November 1957 at Tachikawa AFB, Japan. He graduated from high school in Denver, olorado in 1975. His undergraduate degree was Bachelor of Science, Operations Research, awarded by the U.S. Air Force Academy, 1979. After a two year tour at the Tactical Fighter Weapons Center, Studies and Analysis (1979-1981) he was assigned to the School of Engineering, Air Force Institute of Technclogy.

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